Inorganic Scintillators for Future High Energy Physics Experiments

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Why Inorganic Scintillators?

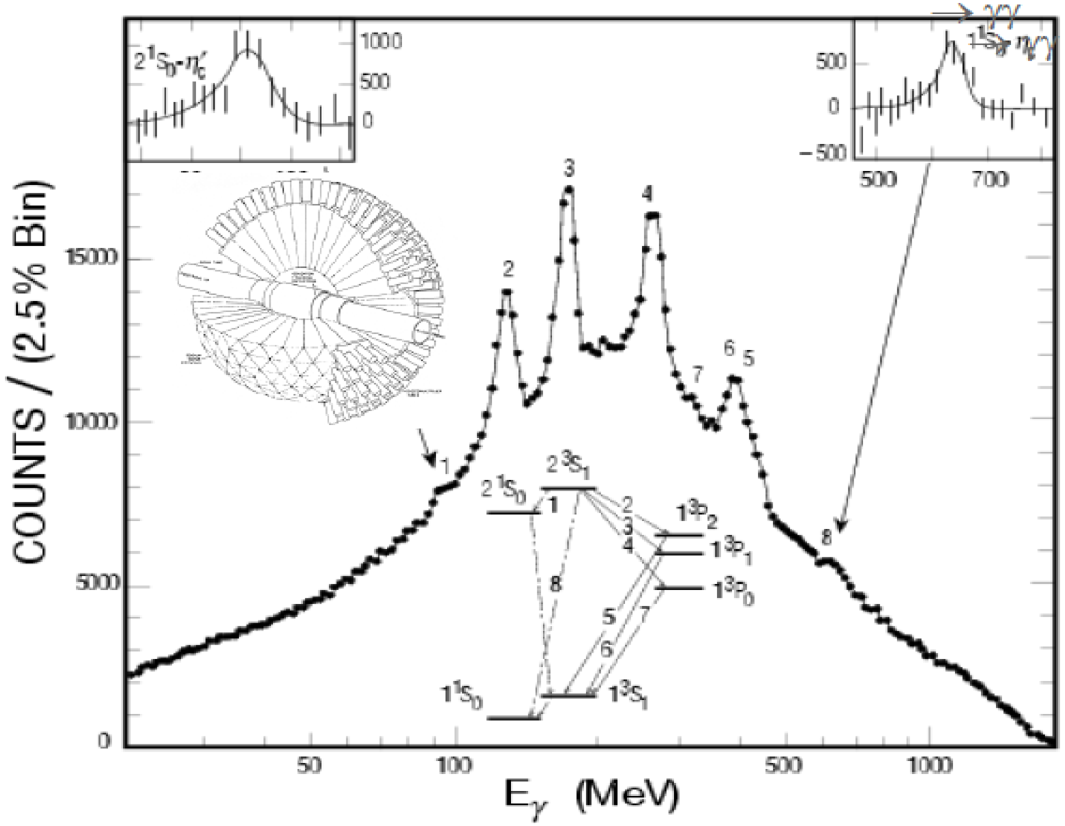
arXiv: 2203.06731 and arXiv: 2203.06788

- **Precision e/γ enhance physics discovery potential.**
- **Performance of total absorption ECAL is well understood for e/γ and jets:**
  - **Energy resolution achieved:** $2\%/\sqrt{E} \oplus 1\%$
  - **Position resolution: sub-mm can be achieved;**
  - **Good identification and reconstruction efficiency;**
  - **Excellent jet mass resolution with dual readout: C/S light or S/L gate.**
- **On-going Development in Caltech Crystal Lab:**
  - **Rad-hard LYSO:Ce crystals and LuAG:Ce ceramics (RADiCAL) for HL-LHC and FCC-hh;**
  - **Ultrafast BaF_2:Y and Lu_2O_3:Yb for future ultrafast calorimetry and time of flight;**
  - **Cost-effective ABS and DSB glasses for Higgs factory (Calvision) and HHCAL.**

Precision e/γ Physics in HEP

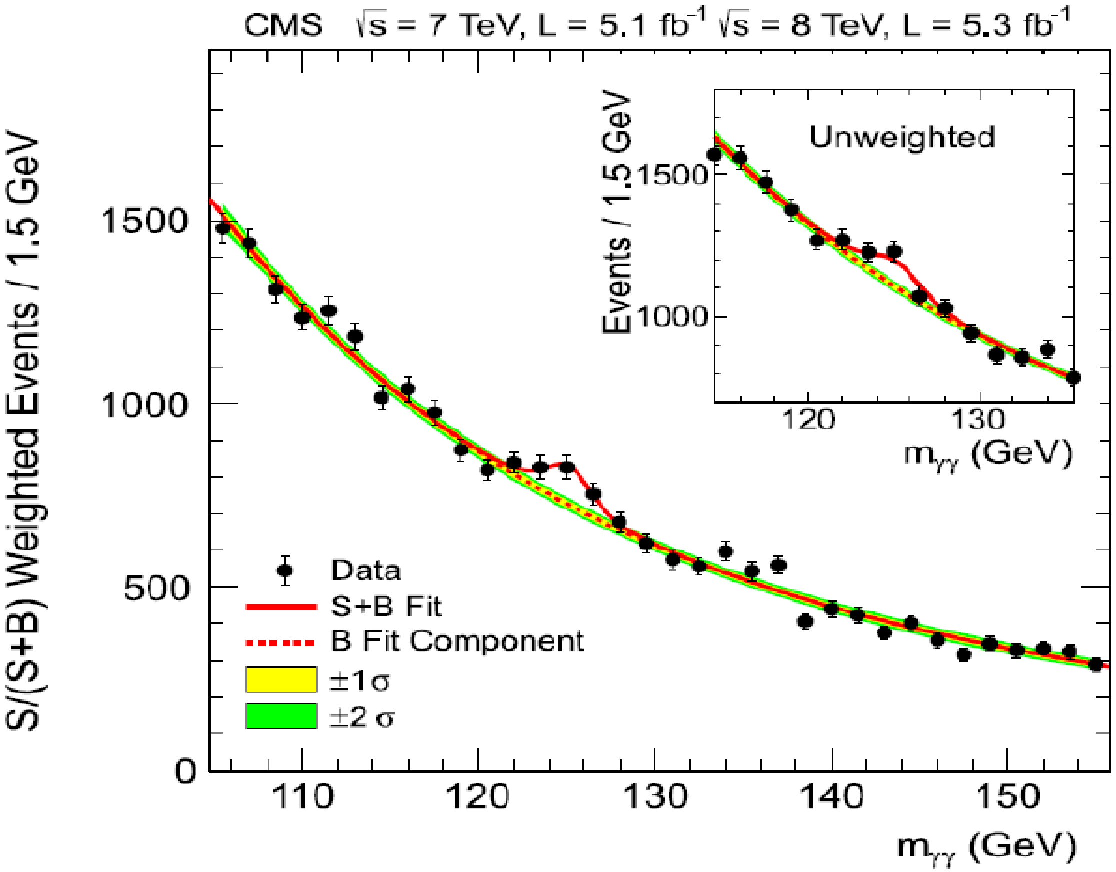
Charmonium system observed by CB through Inclusive photons

CB NaI(Tl)



Higgs -> $\gamma\gamma$ by CMS through reconstructing photon pairs

CMS PWO



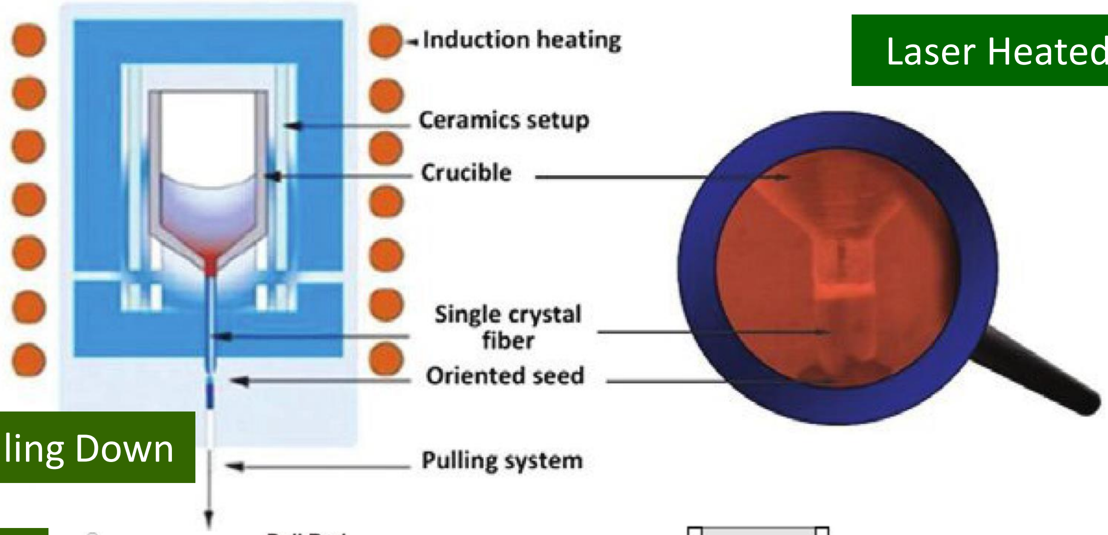
Crystals Used in HEP Calorimeters

Crystal	NaI:Tl	CsI:Tl	CsI	BaF_2	BGO	LYSO:Ce	PWO	PbF_2
Density (g/cm^3)	3.67	4.51	4.51	4.89	7.13	7.40	8.3	7.77
Melting Point (ºC)	651	621	621	1280	1050	2050	1123	824
Radiation Length (cm)	2.59	1.86	1.86	2.03	1.12	1.14	0.89	0.93
Molière Radius (cm)	4.13	3.57	3.57	3.10	2.23	2.07	2.00	2.21
Interaction Length (cm)	42.9	39.3	39.3	30.7	22.8	20.9	20.7	21.0
Refractive Index[a]	1.85	1.79	1.95	1.50	2.15	1.82	2.20	1.82
Hygroscopicity	Yes	Slight	Slight	No	No	No	No	No
Luminescence[b] (nm) (at peak)	410	550	420 310	300 220	480	402	425 420	-
Decay Time[b] (ns)	245	1220	30 6	650 0.9	300	40	30 10	-
Light Yield[b,c] (photons/MeV)	38,000	63,000	1,400 420	13,680 1,560	8,000	32,000	114 40	-
d(LY)/dT[b] (%/ ºC)	-0.2	0.4	-1.4	-1.9 0.1	-0.9	-0.2	-2.5	-
Experiment	Crystal Ball	BaBar BELLE BES III	KTeV Mu2e S. BELLE	TAPS Mu2e-II?	L3 BELLE	COMET CMS BTL PIONEER	CMS ALICE PANDA EIC	A4 G-2

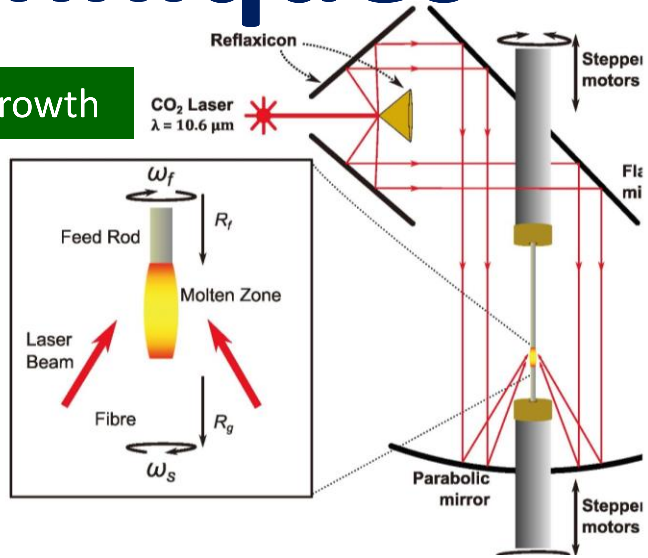
a. at emission peak; b. up/low row: slow/fast component; c. with QE of readout device taken out.

Crystal Growth Techniques

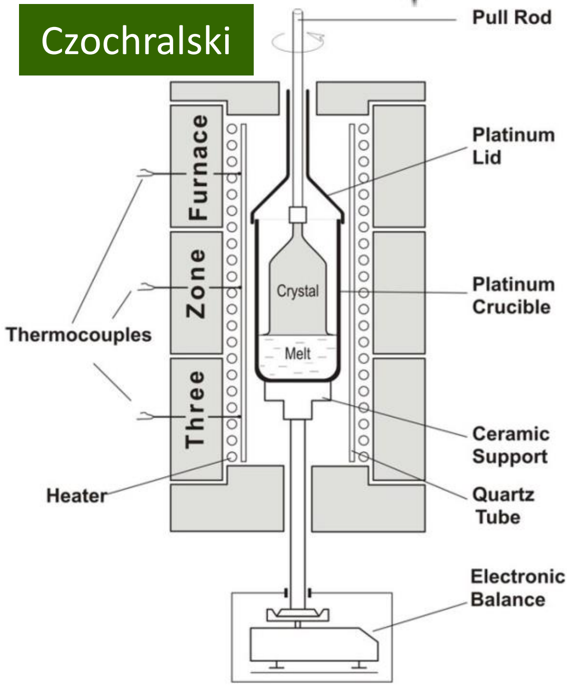
Micro-Pulling Down



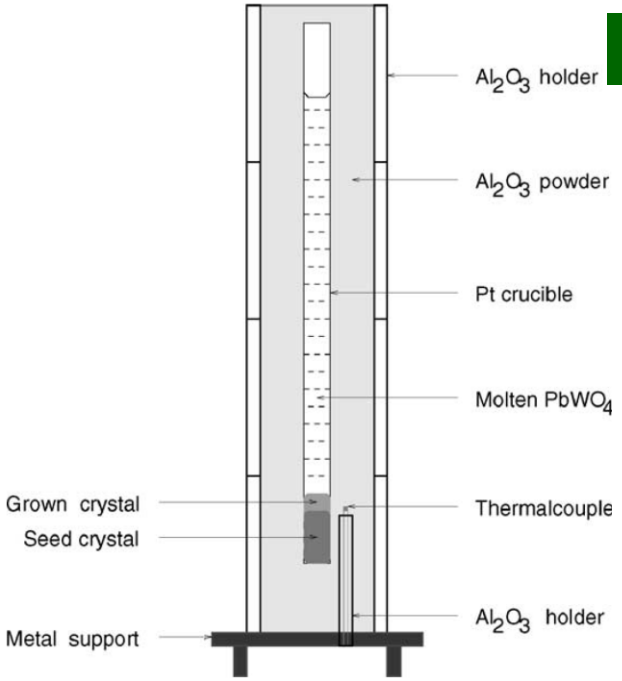
Laser Heated Pedestal Growth

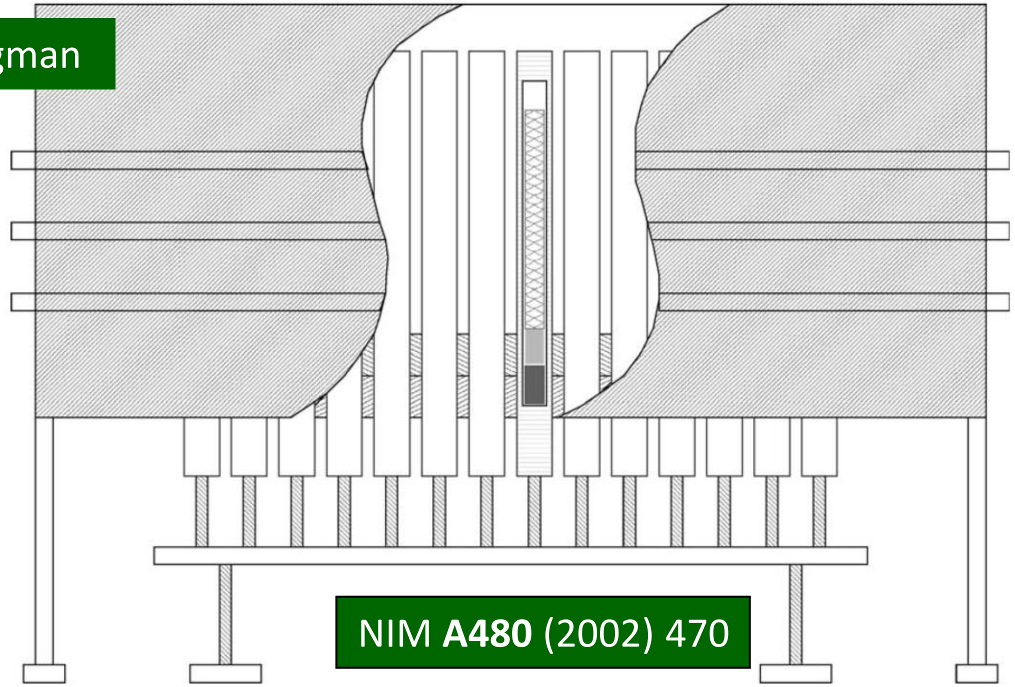


Czochralski



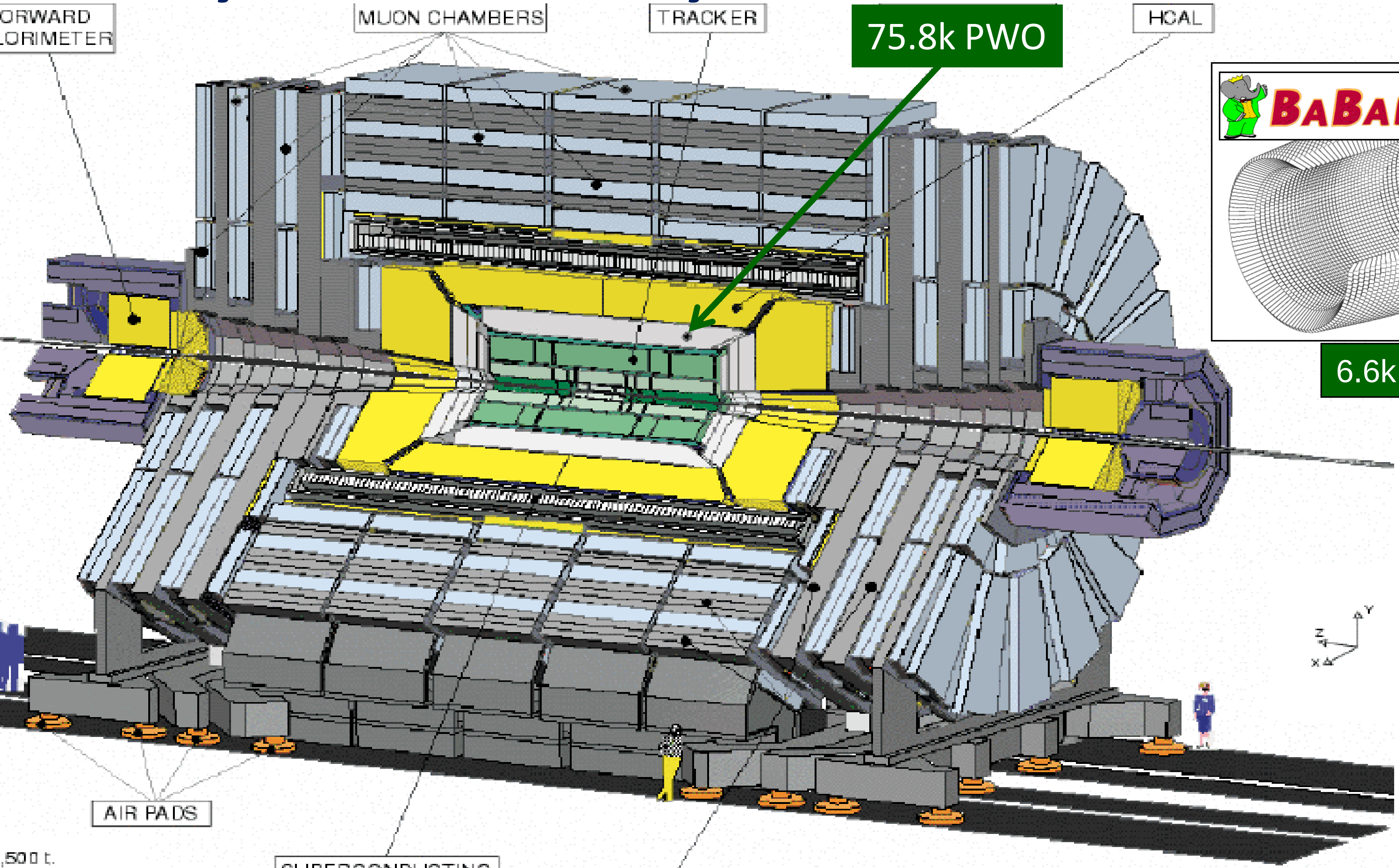
Bridgman

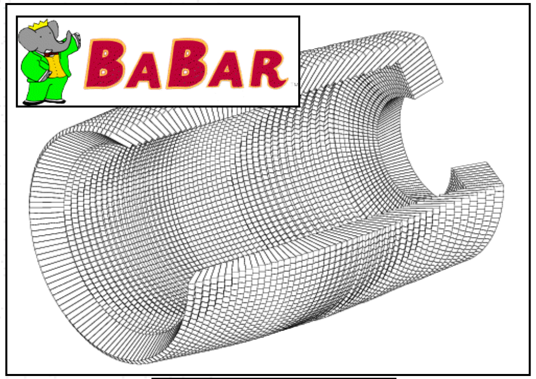




NIM **A480** (2002) 470

L3 BGO, BaBar CsI, CMS PWO ECAL





Dose Rate Dependent Damage in PWO

PWO light reached an equilibrium under a dose rate, showing a dose rate dependent damage
Damage/recovery requires continuous light monitoring to maintain PWO energy resolution

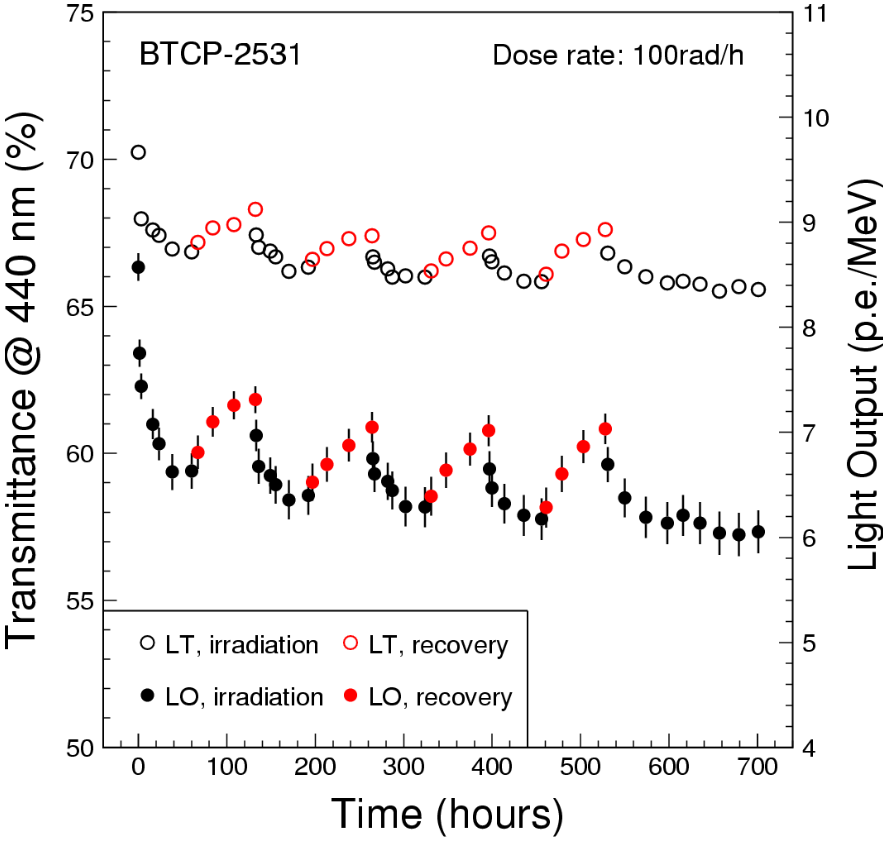
Damage/recovery observed in early lab investigation:
IEEE Trans. Nucl. Sci., Vol. 44 (1997) 458-476

$$dD = \sum_{i=1}^{n} \{-a_i D_i dt + (D_i^{all} - D_i)\, b_i R dt\}$$

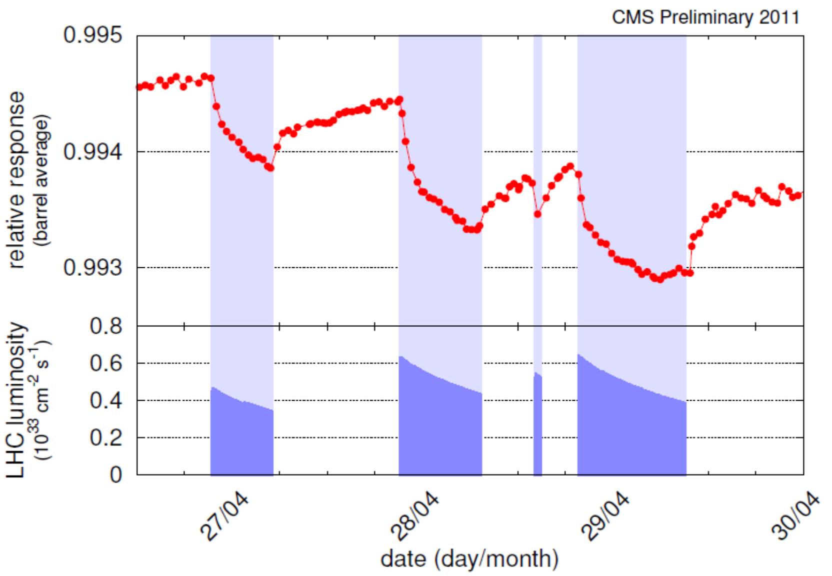
$$D = \sum_{i=1}^{n} \{ \frac{b_i R D_i^{all}}{a_i + b_i R} [1 - e^{-(a_i + b_i R)t}] + D_i^0 e^{-(a_i + b_i R)t} \}$$

- D_i: color center density in units of m^{-1};
- D_i^0: initial color center density;
- D_i^{all} is the total density of trap related to the color center in the crystal;
- a_i: recovery costant in units of hr^{-1};
- b_i: damage contant in units of kRad^{-1};
- R: the radiation dose rate in units of kRad/hr.

$$D_{eq} = \sum_{i=1}^{n} \frac{b_i R D_i^{all}}{a_i + b_i R}$$



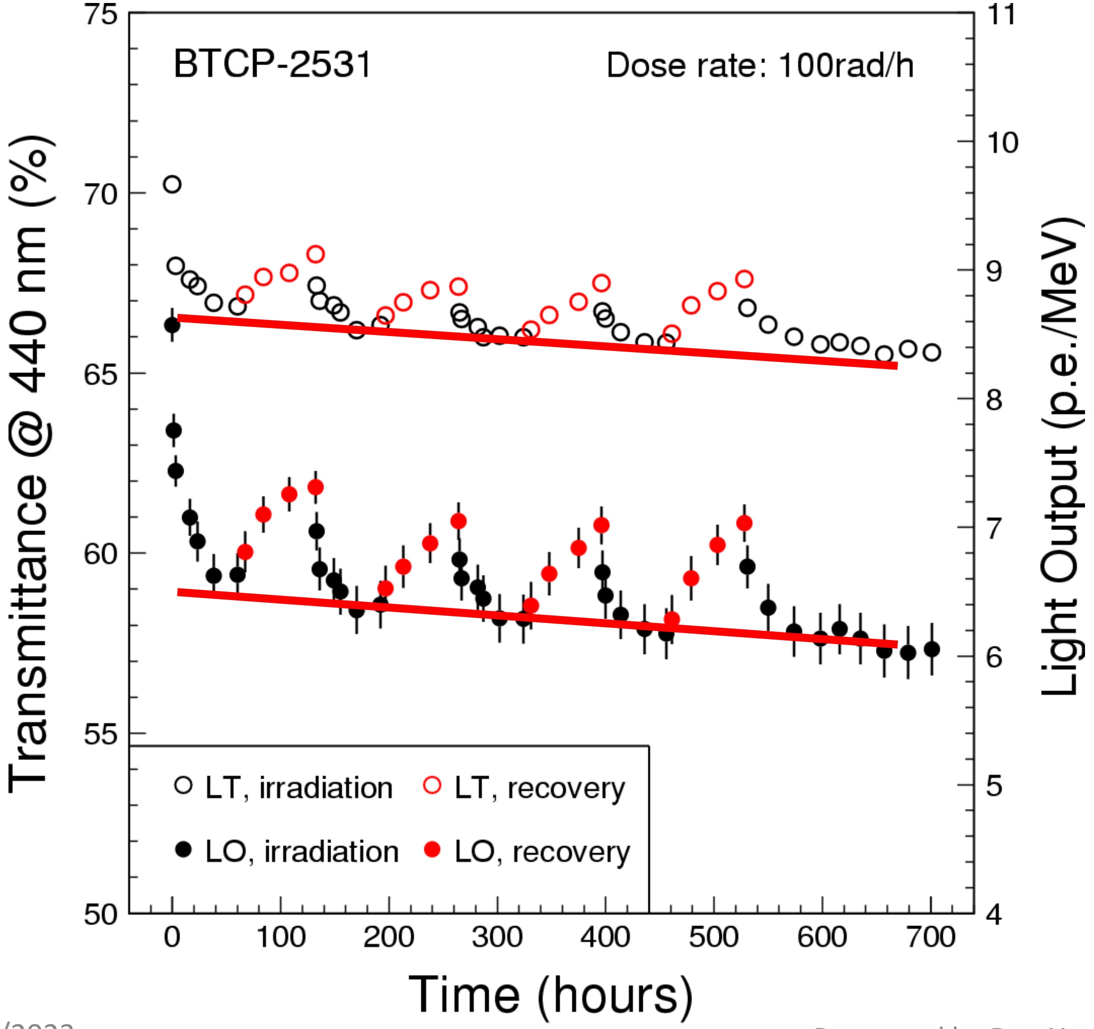
Damage and recovery observed *in situ* at the LHC by the CMS light monitoring system

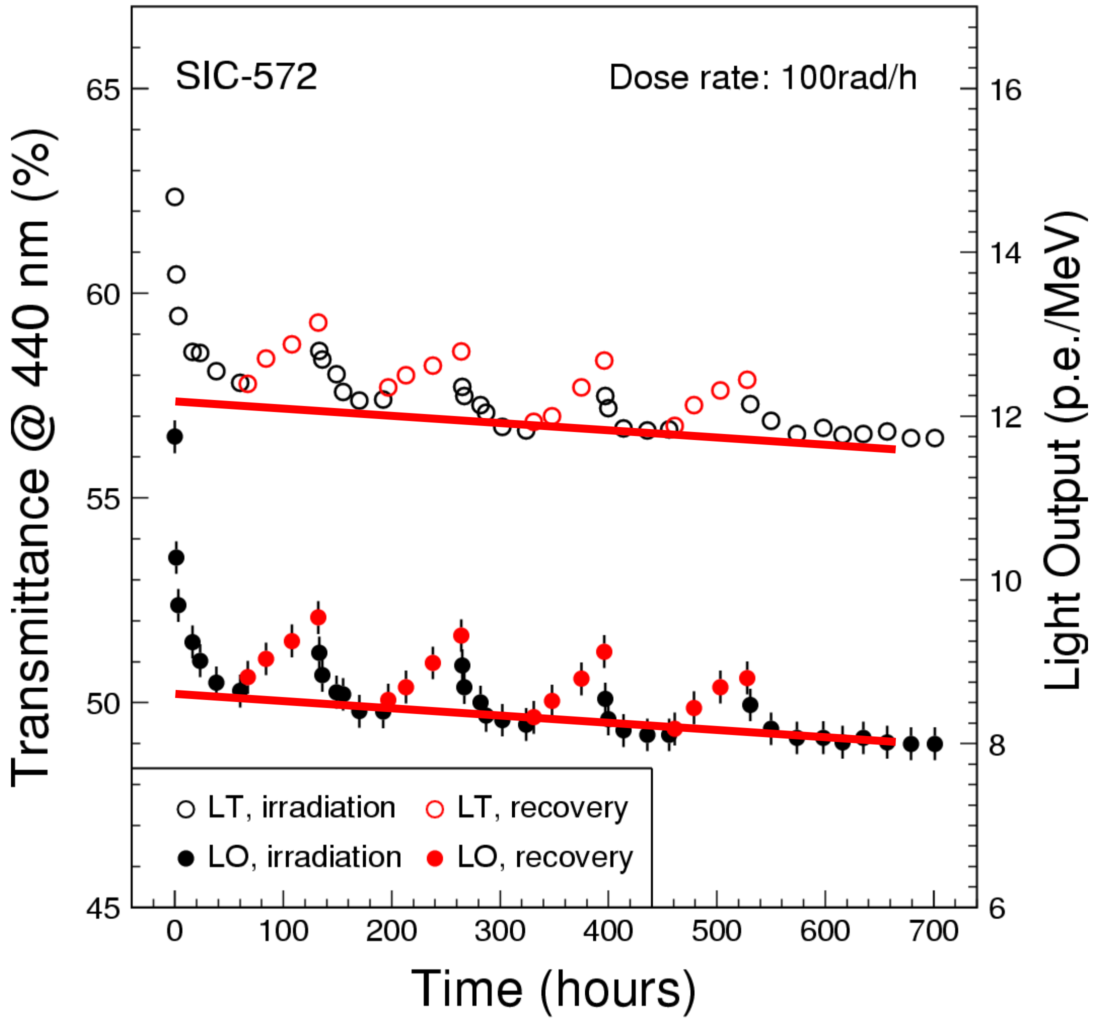


Effect of Multiple Color Centers

BTCP & SIC PWO @ 100 rad/h and recovery

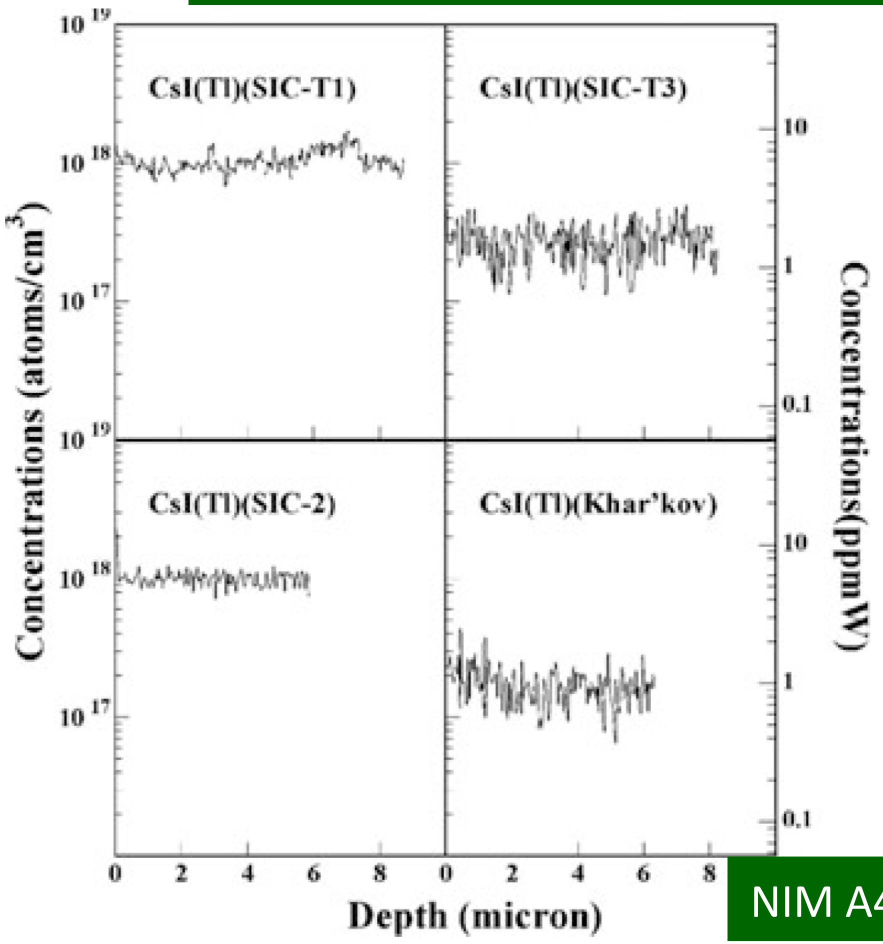
AIP Conference Proceedings 867 (2006) 252





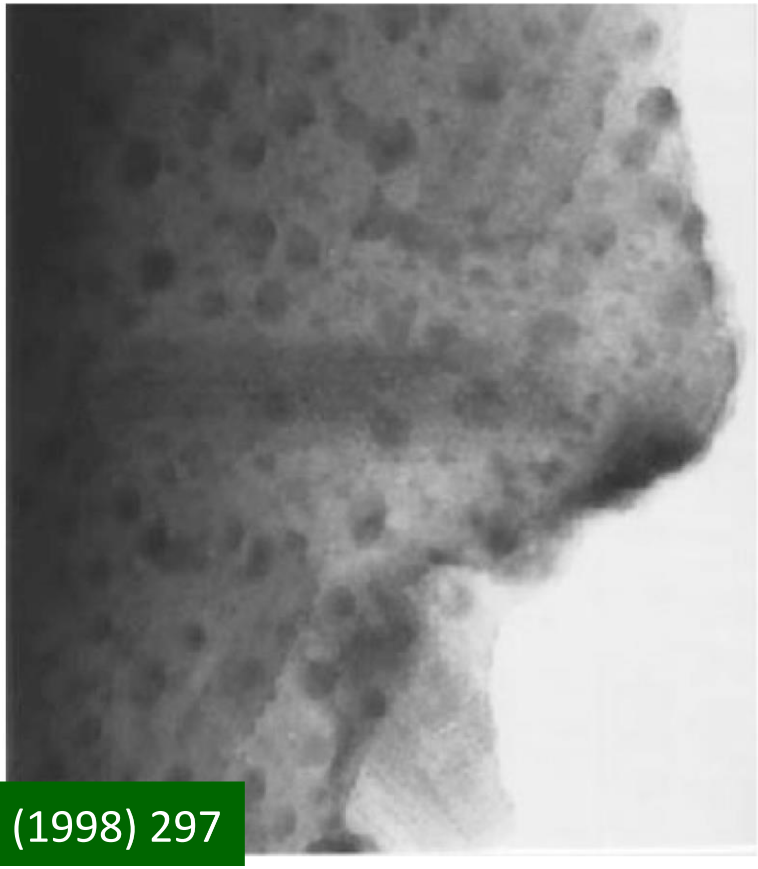
Radiation Damage Mechanism

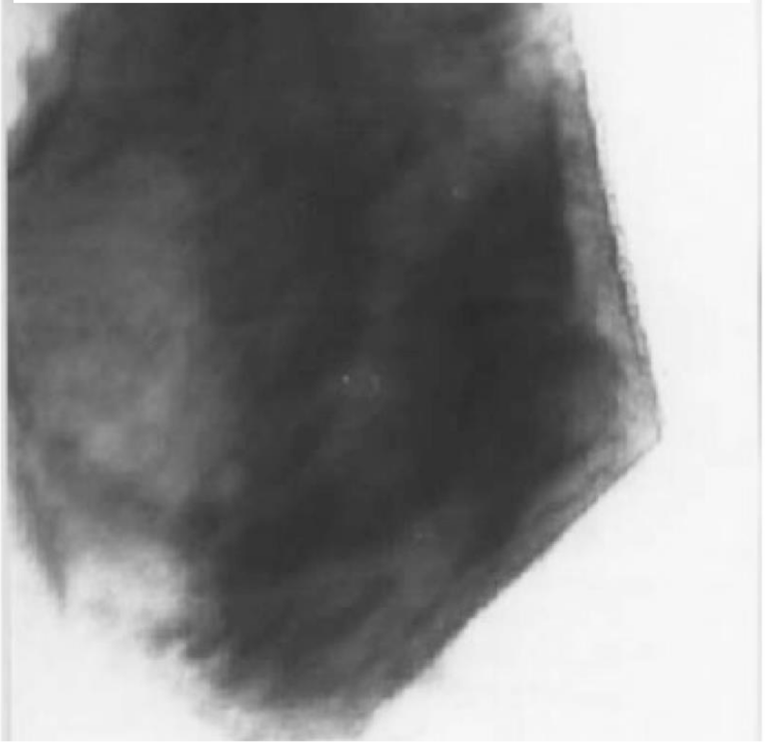
SIMS analysis revealed that damage in alkali halides was caused by the oxygen and/or hydroxyl contamination. Localized stoichiometry analysis by TEM/EDS revealed that damage in oxides was caused by stoichiometry-related defects, e.g. oxygen vacancies.



NIM A413 (1998) 297

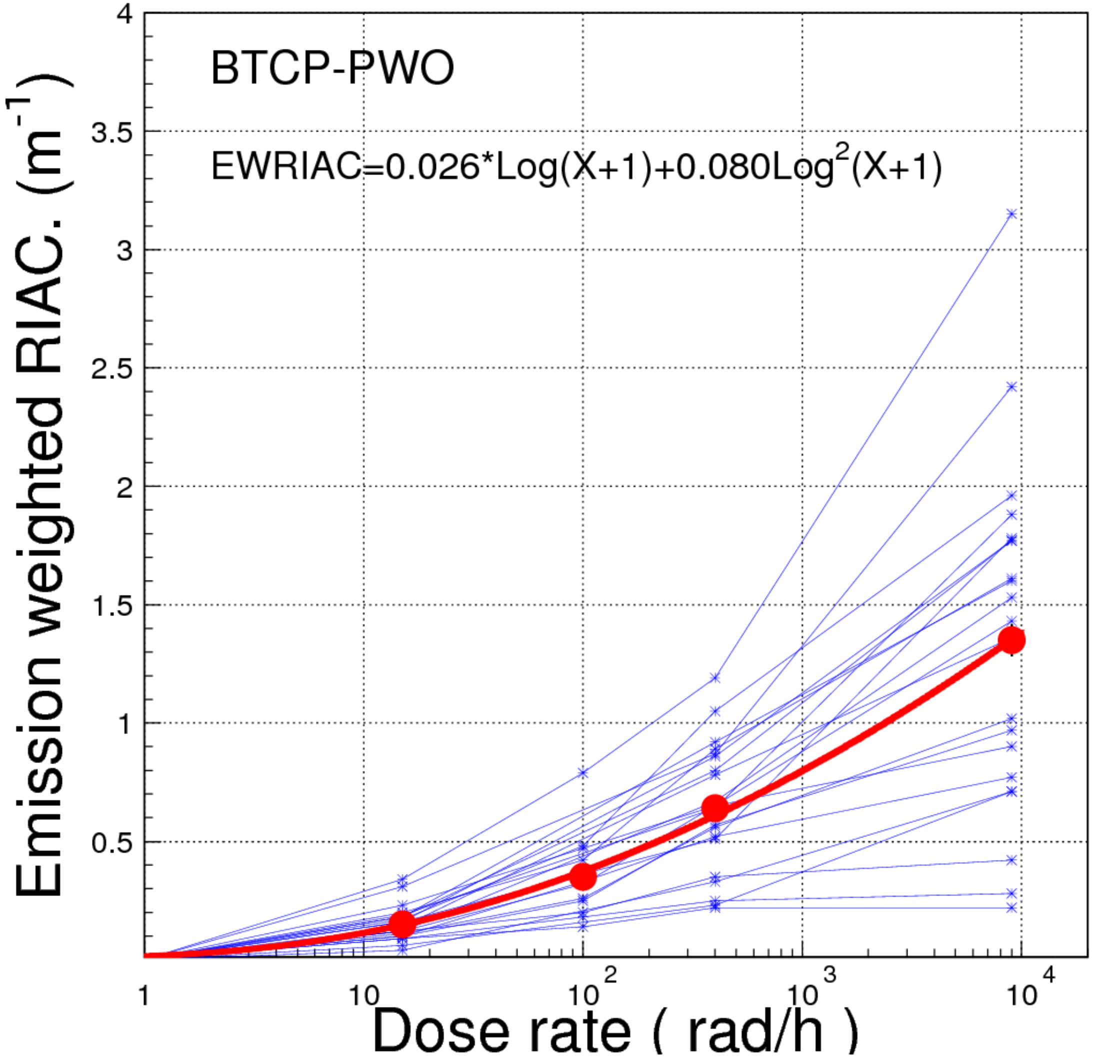
As grown sample				
Element	Black spot	Peripheral	$Matrix_1$	$Matrix_2$
O	1.5	15.8	60.8	63.2
W	50.8	44.3	19.6	18.4
Pb	47.7	39.9	19.6	18.4
The same sample after oxygen compensation				
Element	$Point_1$	$Point_2$	$Point_3$	$Point_4$
O	59.0	66.4	57.4	66.7
W	21.0	16.5	21.3	16.8
Pb	20.0	17.1	21.3	16.5

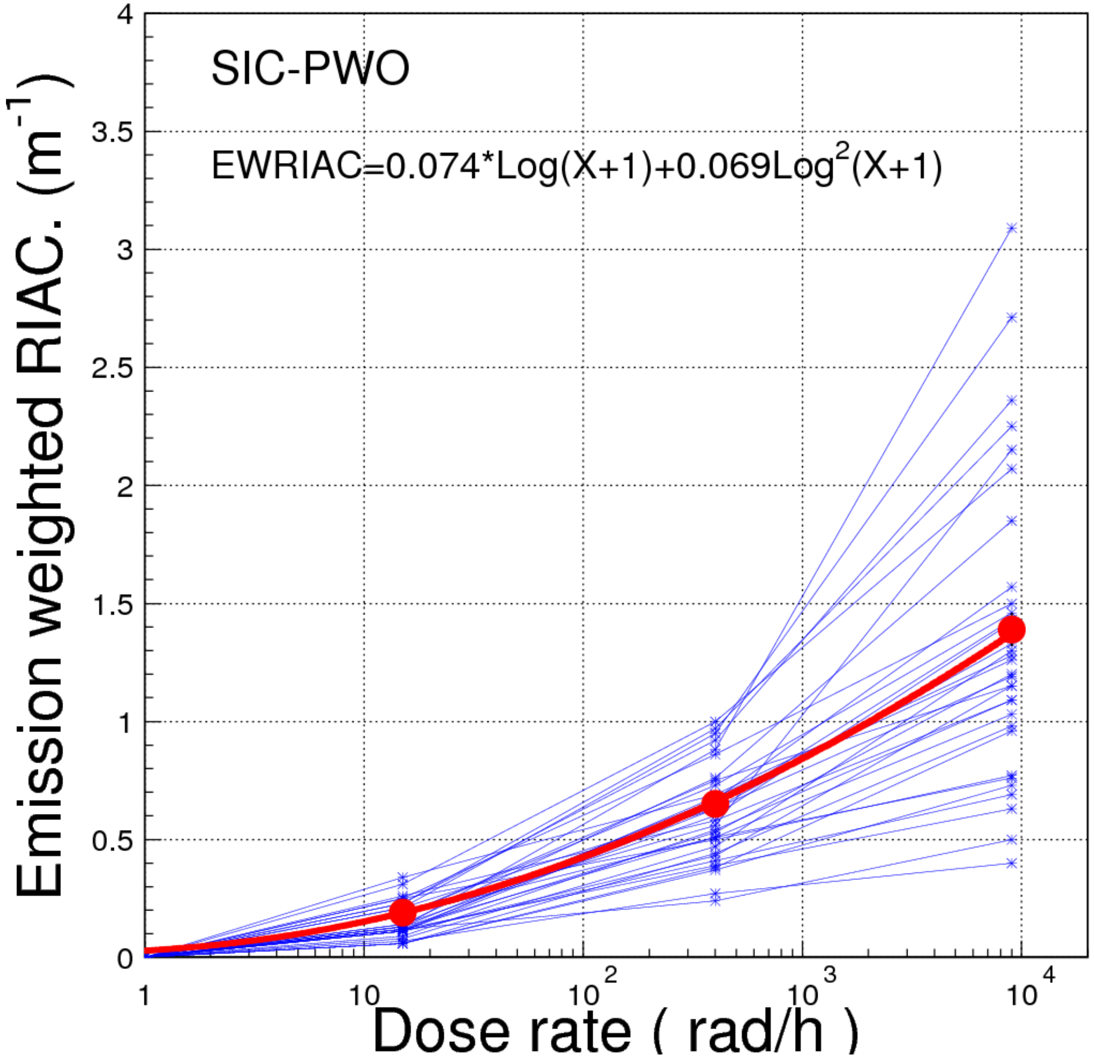




EWRIAC vs. Ionization Dose Rate

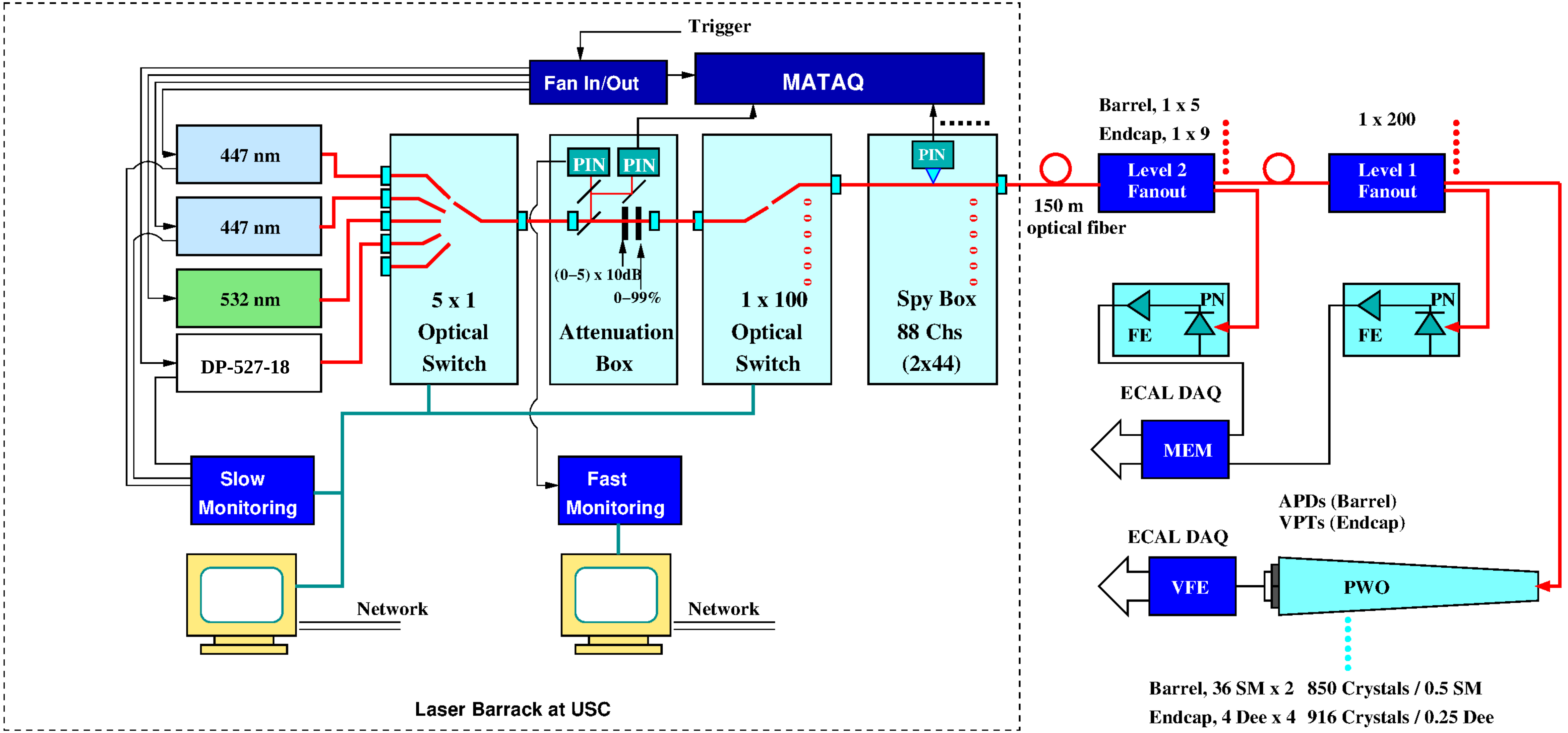
Large spread observed for both BTCP and SIC PWO with EWRIAC fit to 2nd order polynomials of dose rate. IEEE Trans. Nucl. Sci. NS-51 (2004) 1777





CMS PWO ECAL Laser Monitoring

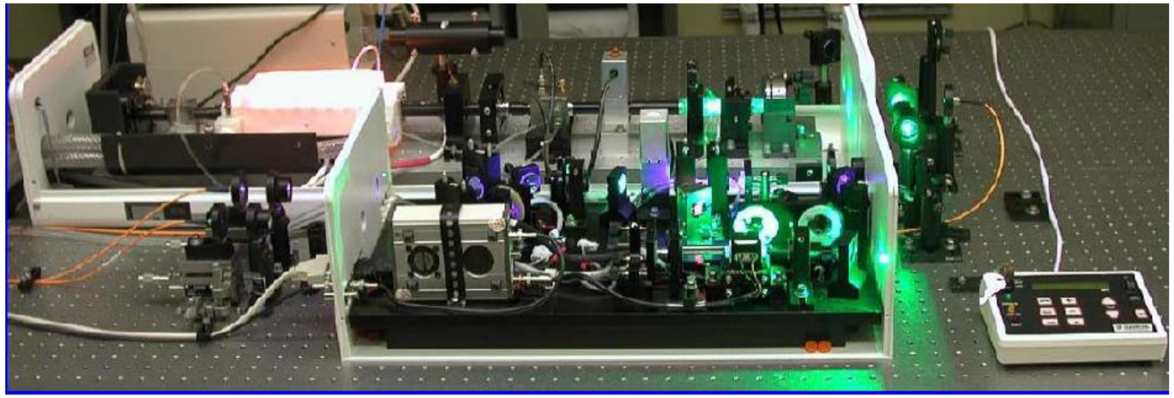
Runs 24/7 providing 600 laser pulses/crystal at 100 Hz every 30 min

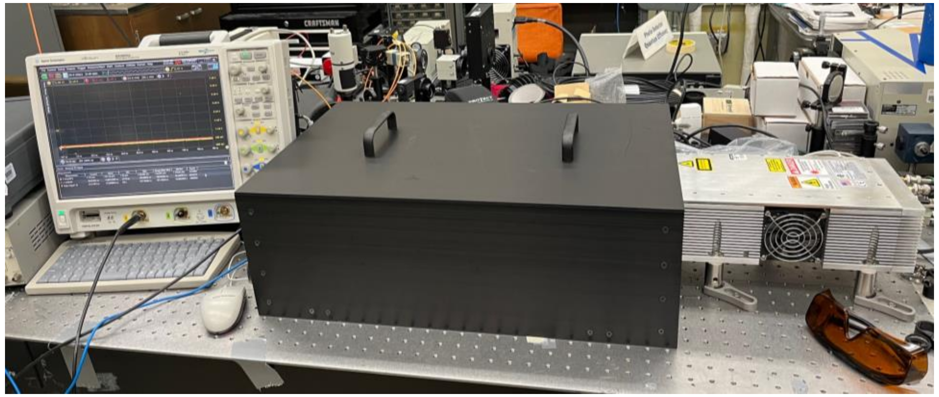


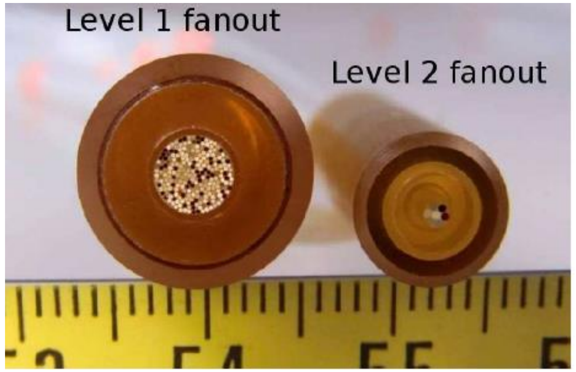
CMS Laser Monitoring Hardware

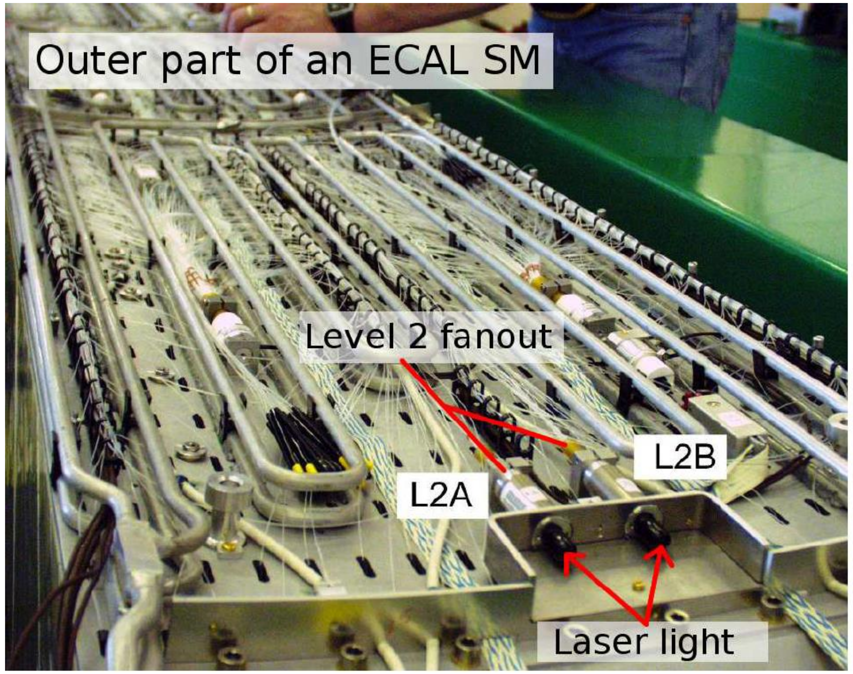
Lamp Pumped Lases: 2002 to 2012

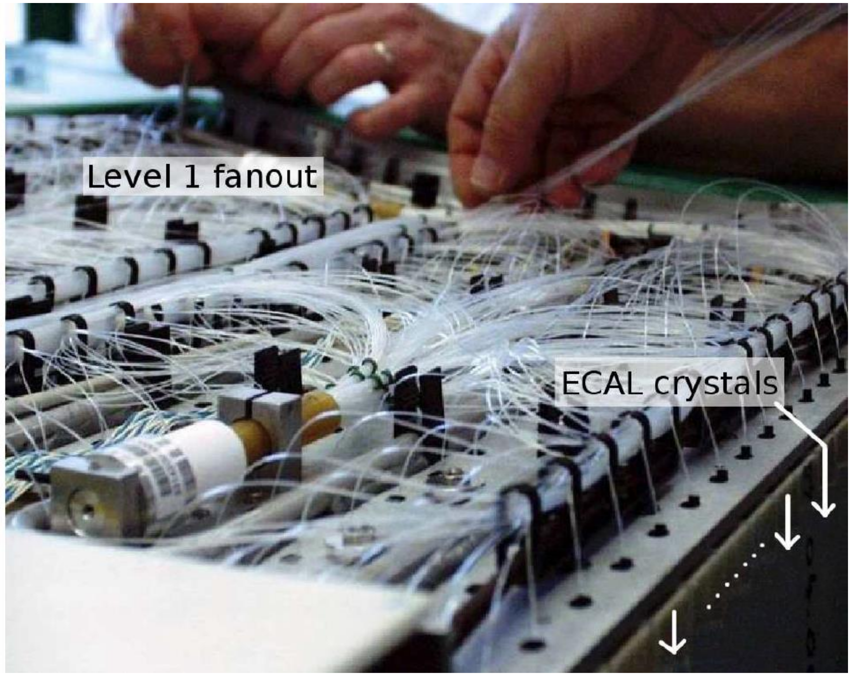
Diode Pumped Lases: since 2012





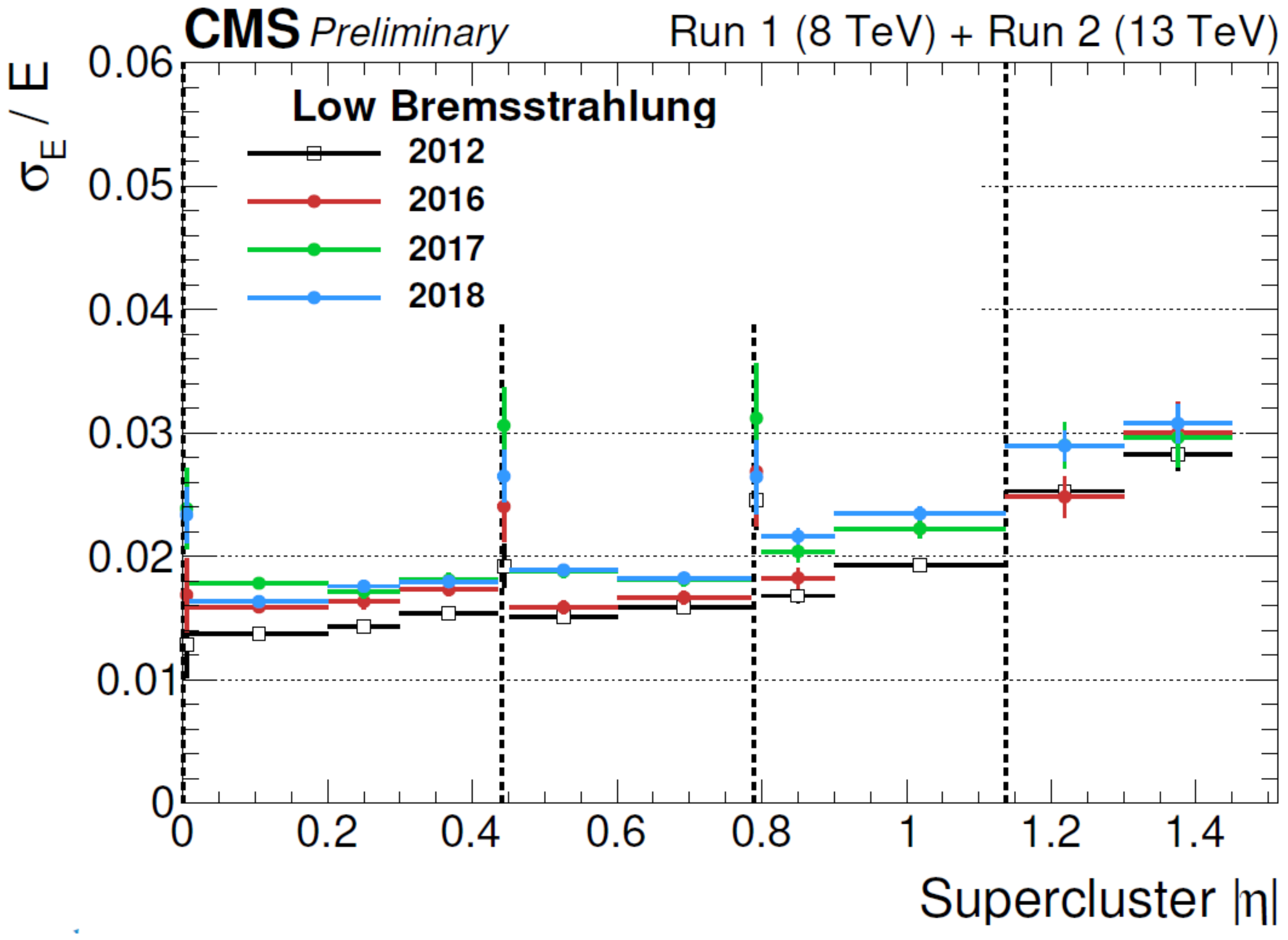


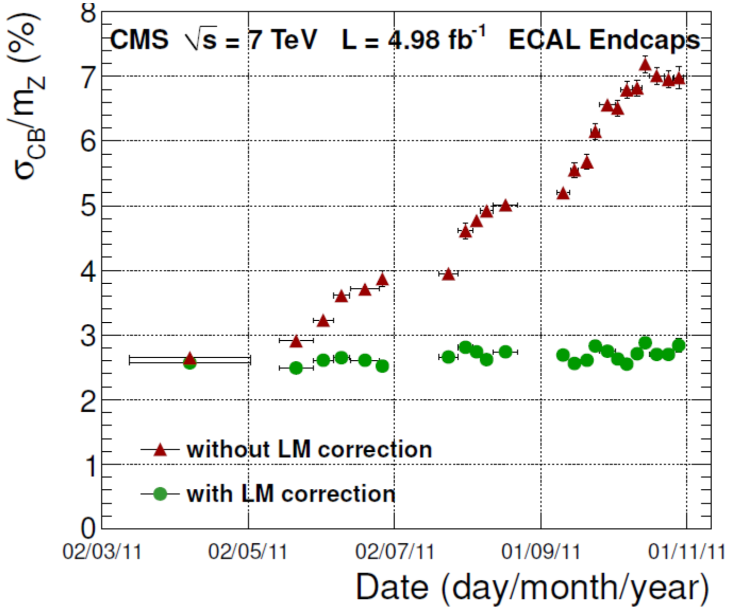


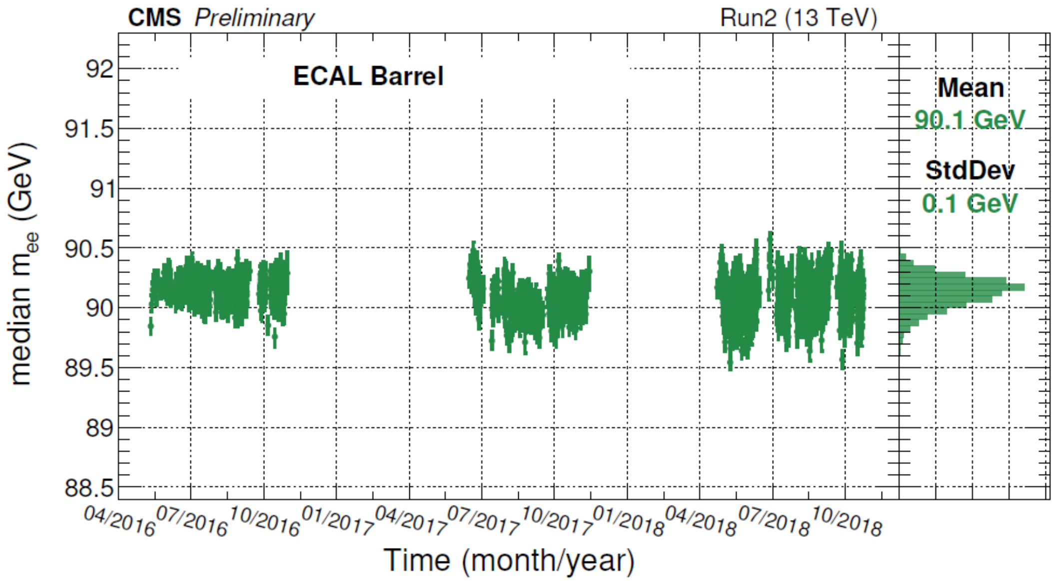


CMS ECAL Performance at LHC

Degradation of energy resolution due to radiation damage
F. Ferri, presented in Calor 2022, Brighton

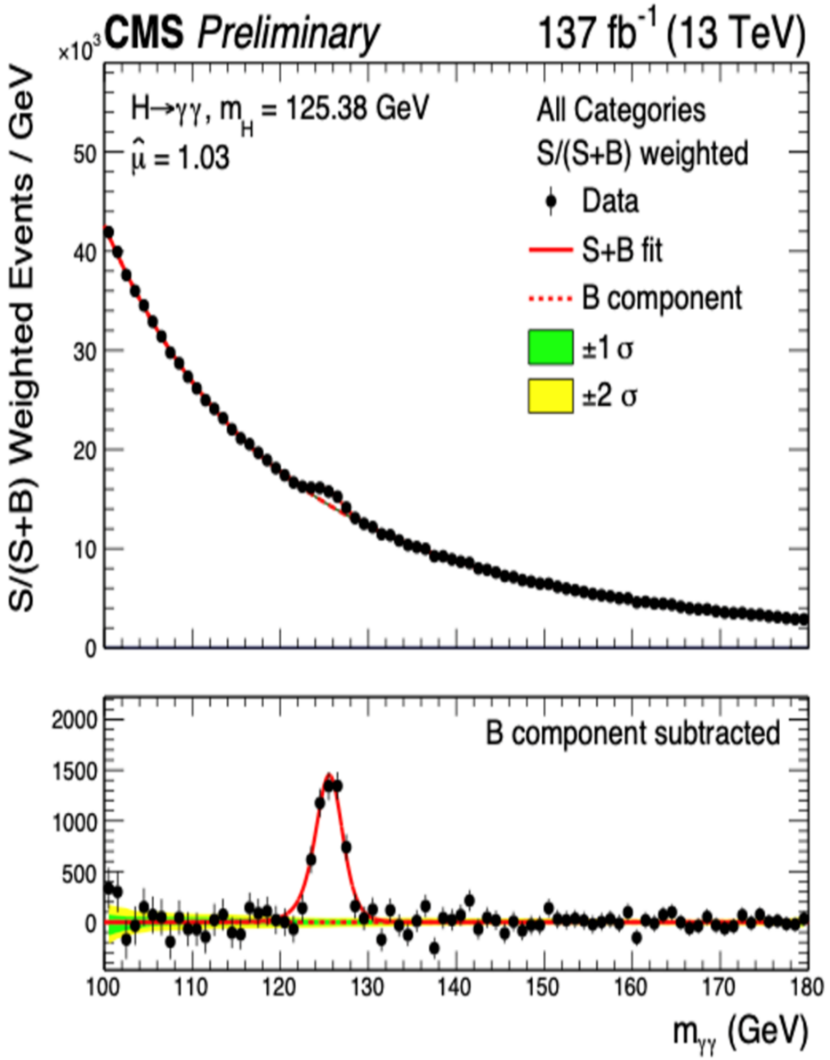


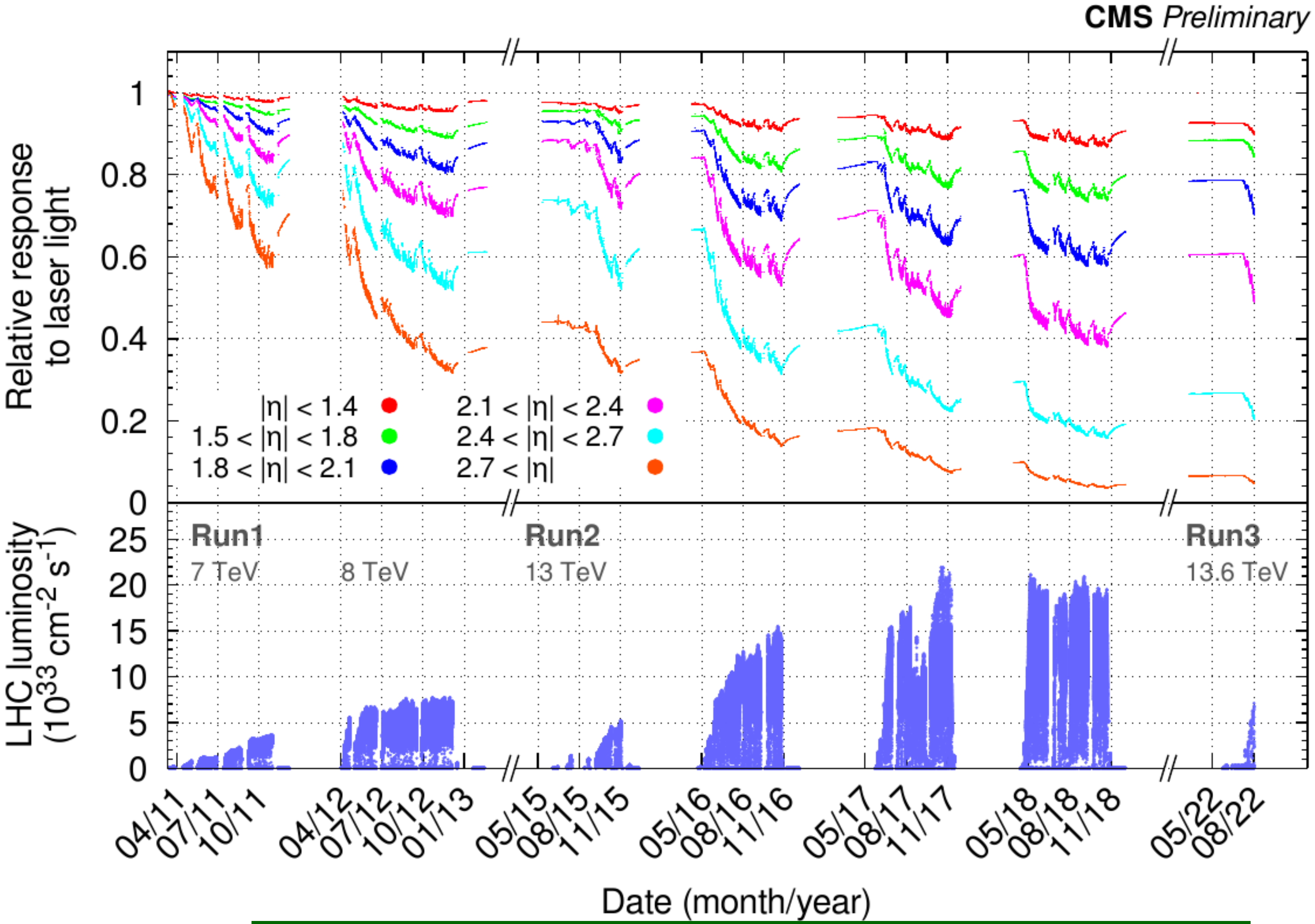




CMS H -> γγ and PWO Damage

T. Dimova, TIPP2023, light monitoring data





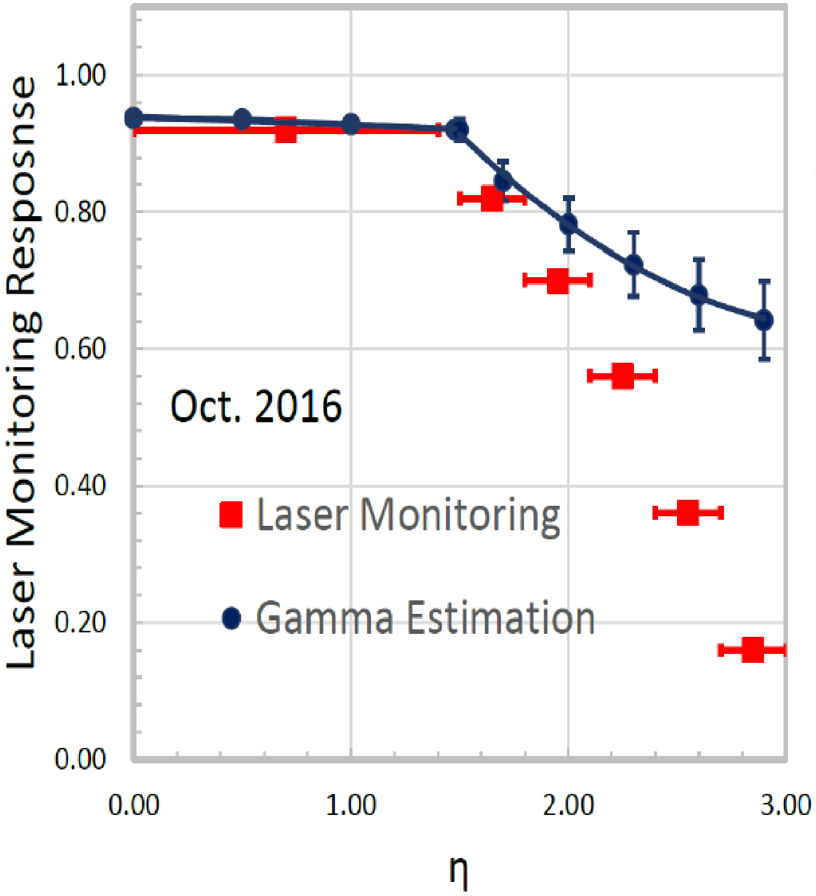
PWO damage due to ionization dose and hadrons

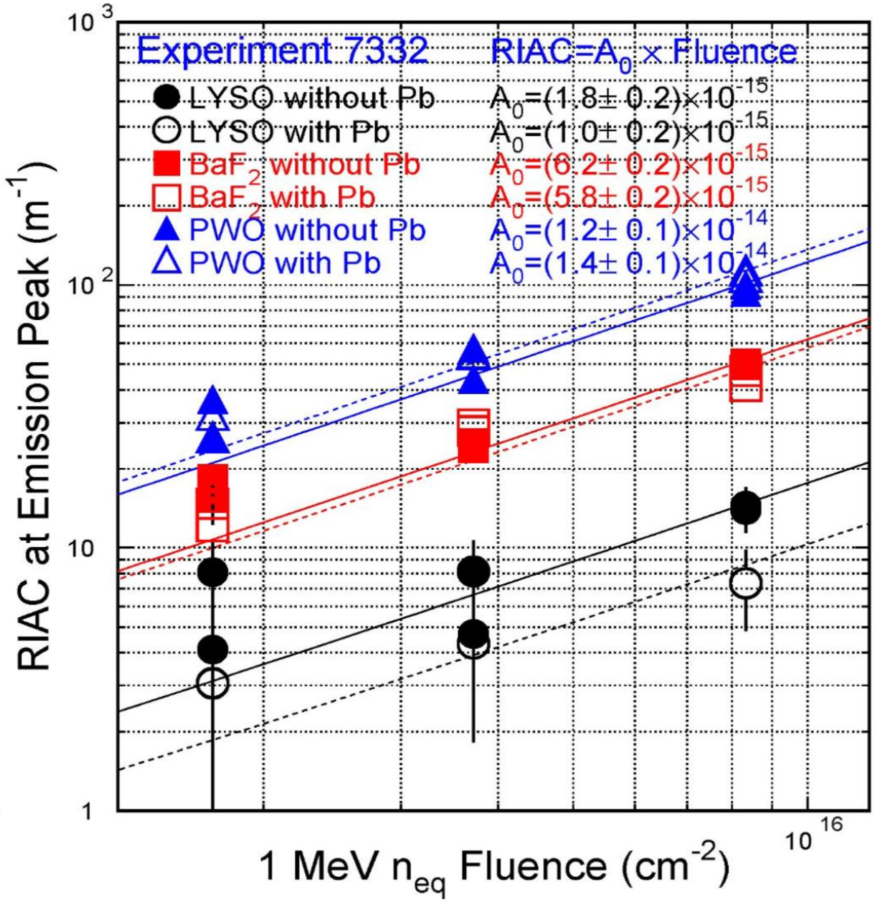
PWO Damage by Ionization & Neutrons

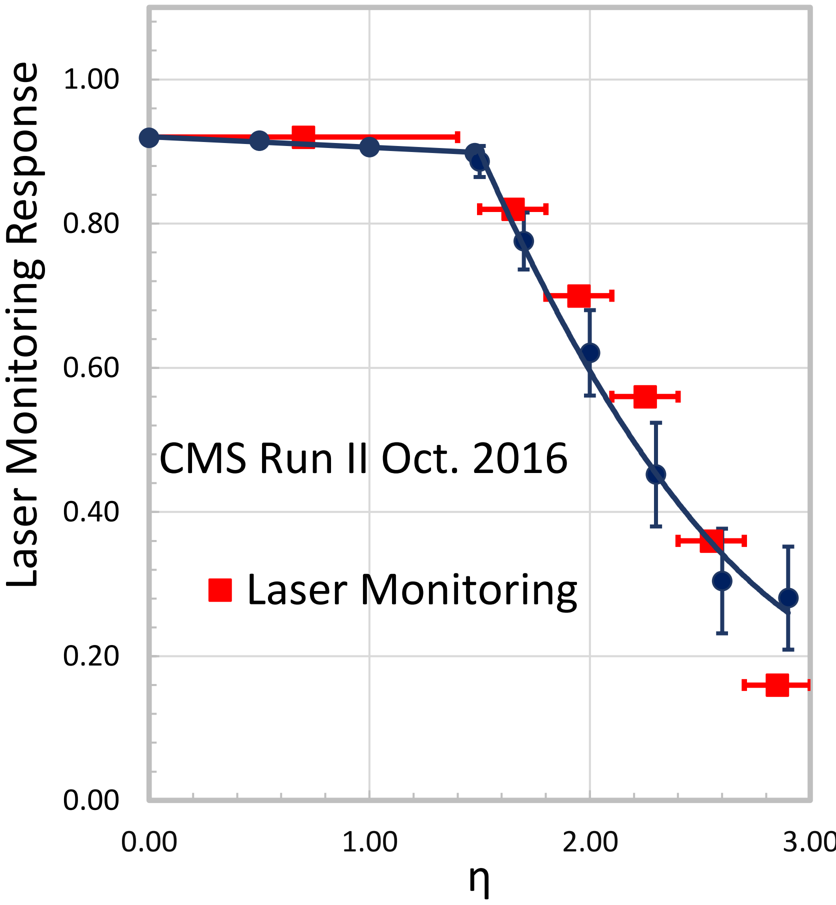
RIAC in PWO = $1.4 \times 10^{-14} \times$ 1 MeV n_{eq} Fluence

γ-ray and hadron induced absorption explains CMS PWO monitoring data

http://www.its.caltech.edu/~rzhu/talks/ryz_161028_PWO_mon.pdf & Trans. NS. 67 (2020) 1086-1092







Comparison: ePIC and BTL at HL-LHC

The ionization dose rate and neutron flux of the ePIC PWO ECAL are two to three orders of magnitude lower than that of the CMS BTL (LYSO:Ce+SiPM) at the HL-LHC
The expected RIAC values are small. QC is needed for mass-produced PWO crystals

Radiation	EIC / Year	EIC*	CMS BTL** / 4000 fb-1 (η= 0-1.45)	CMS BTL** (η= 0-1.45)
Ionization Dose	3 Krad	1.3 rad/h	2.7-4.8 Mrad	110-190 rad/h
1 MeV eq. Neutrons	10^{10} /cm^2	1.2×10^3 /cm^2/s	(2.5~2.9)×10^{14} /cm^2	(2.8~3.2)×10^6 /cm^2/s
Charged Hadrons			(2.2~2.5)×10^{13} /cm^2	(2.4~2.8)×10^5 /cm^2/s

*Estimated by assuming 100 days operation per year.
** IEEE Trans. Nucl. Sci. NS-68 (2021) 1244-1250

2019 DOE Basic Research Needs Study
Priority Research Directions for Calorimetry

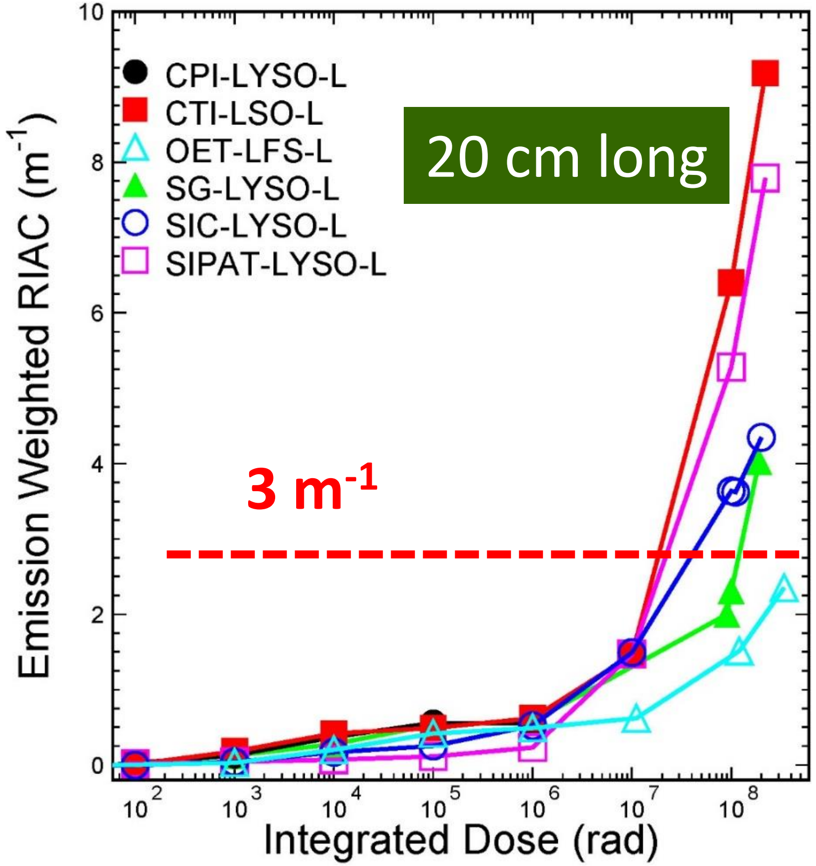
- Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements;
- Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments;
- Develop ultrafast media to improve background rejection in calorimeters and particle identication detectors.

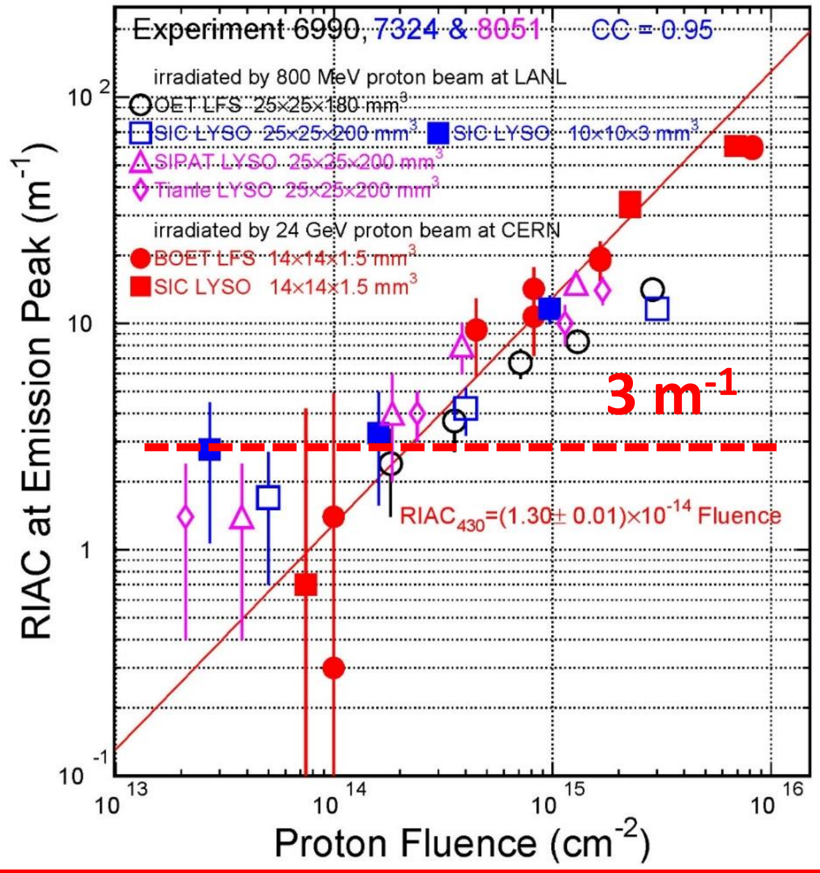
DOE 2019: https://www.osti.gov/servlets/purl/1659761
ECFA 2021: https://cds.cern.ch/record/2784893
Snowmass 2021: https://arxiv.org/abs/2209.14111
Fast/ultrafast, radiation hard and cost-effective inorganic scintillators

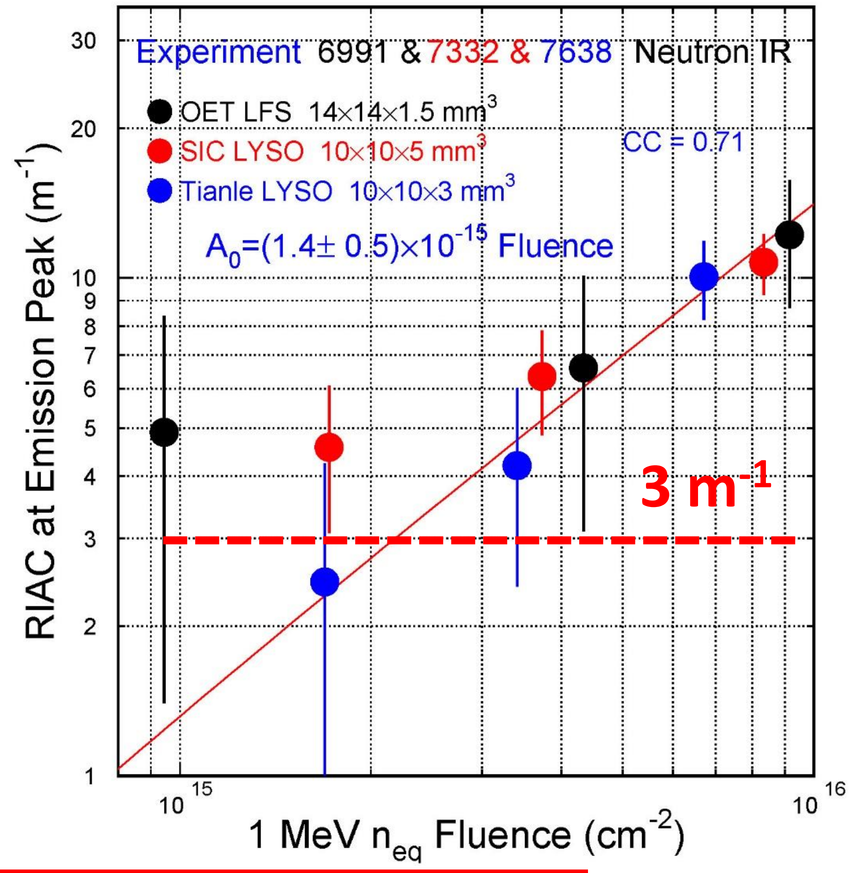
LYSO:Ce Radiation Hardness

IEEE TNS 63 (2016) 612-619

CMS BTL LYSO spec: RIAC < 3 m^{-1} after 4.8 Mrad, 2.5 x 10^{13} p/cm^2 and 3.2 x 10^{14} n_{eq}/cm^2







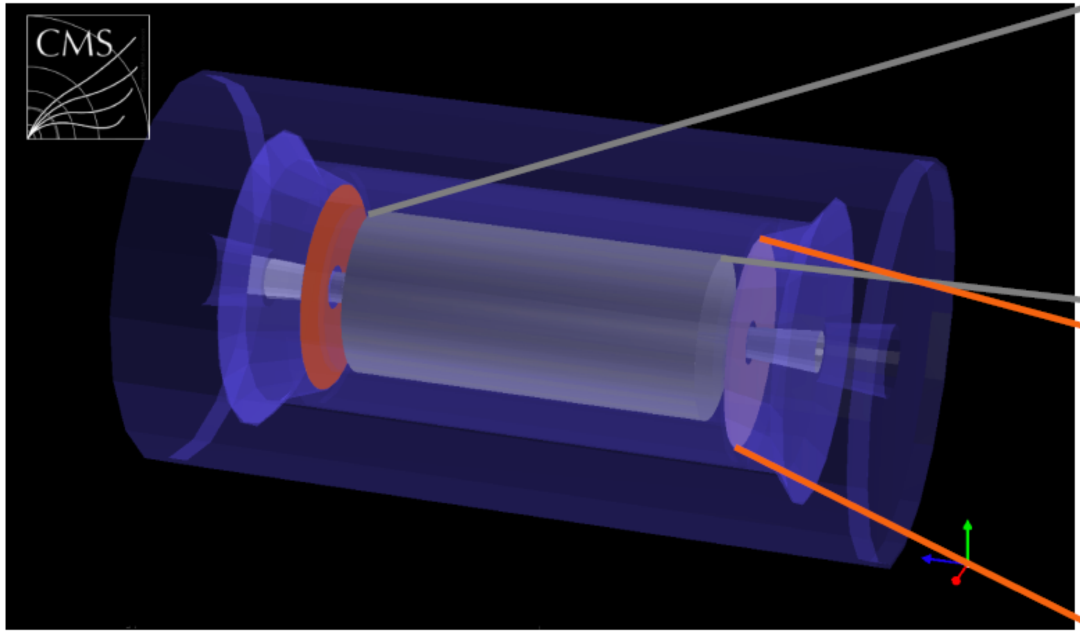
Damage induced by protons is larger than that from neutrons
Due to ionization energy loss in addition to displacement and nuclear breakup

LYSO:Ce for CMS MIP Timing Detector

MTD performance goal: 30-40 ps at the start degrading to < 60 ps at 3000 fb^{-1}

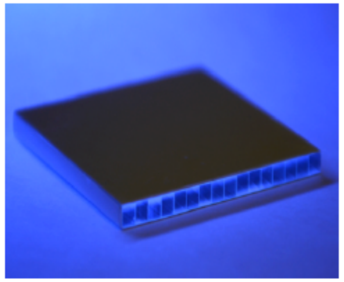
Barrel Timing Layer: arrays of LYSO crystal bars connected to SiPMs at both ends and readout by TOFHIR

Ultrafast inorganic scintillators would help to break the pico-second time barrier



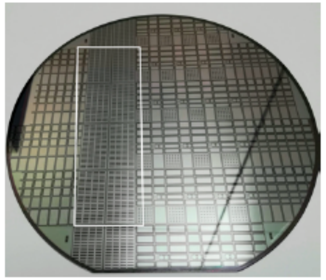
BTL: LYSO bars + SiPM read-out

- TK / ECAL interface ~ 45 mm thick
- $|\eta| < 1.45$ and $p_T > 0.7$ GeV
- Active area ~ 38 m^2 ; 332k channels
- Fluence at 3 ab^{-1}: 2×10^{14} n_{eq}/cm^2



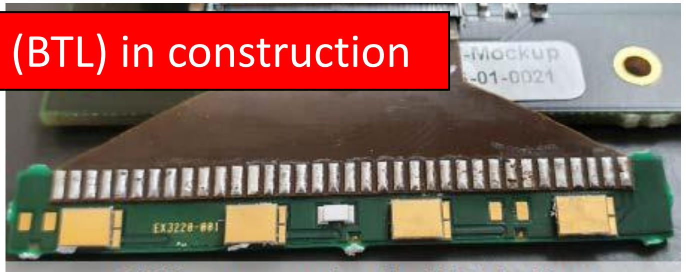
ETL: Si with internal gain (LGAD)

- On the HGC nose ~ 65 mm thick
- $1.6 < |\eta| < 3.0$
- Active area ~ 14 m^2; ~ 8.5M channels
- Fluence at 3 ab^{-1}: up to 2×10^{15} n_{eq}/cm^2



LYSO + SiPM with Thermal Electric Cooler (TEC) for CMS Barrel Timing Layer (BTL) in construction

SiPM array prototypes from FBK

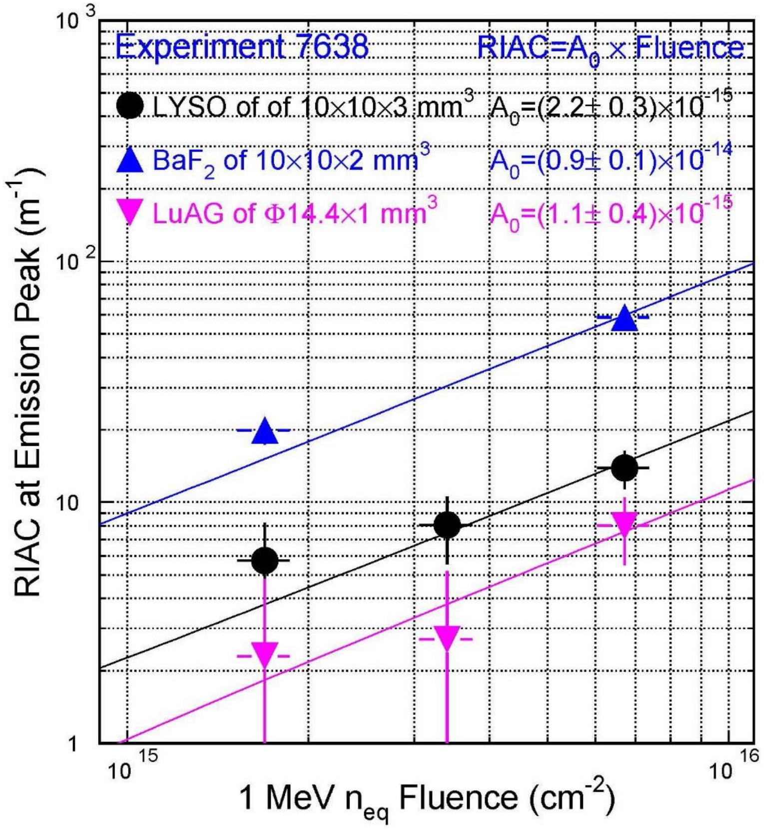


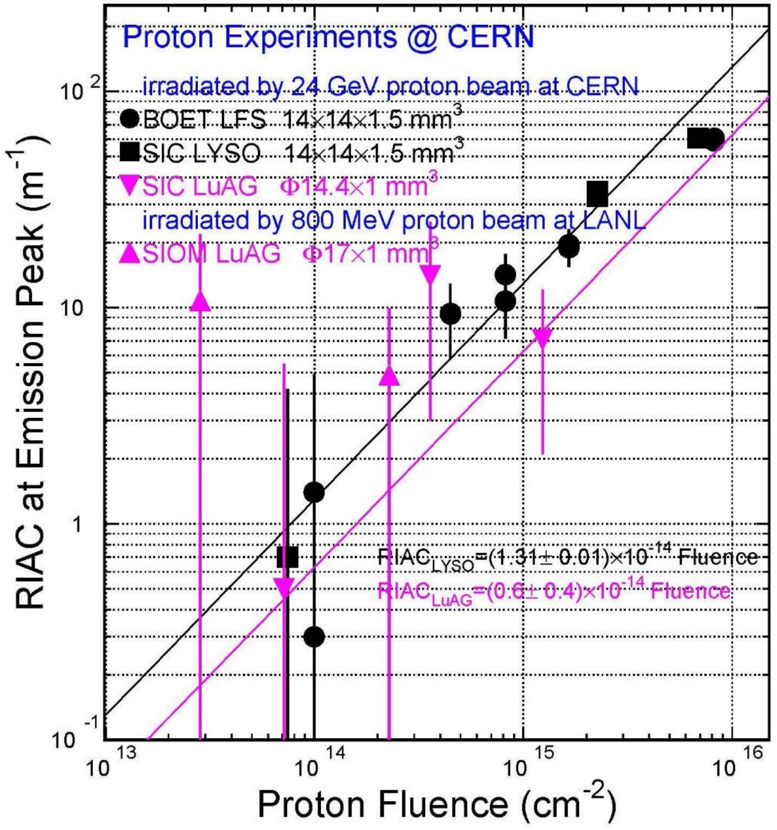
SiPM arrays mockup for TECs testing

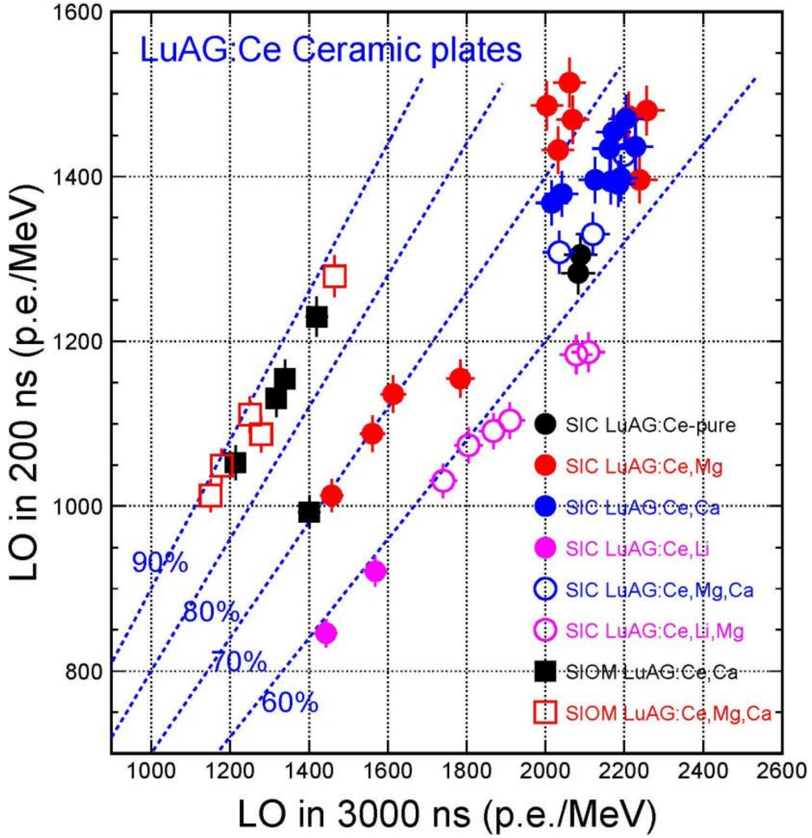
LuAG:Ce Ceramics Radiation Hardness

IEEE TNS 69 (2022) 181-186

LuAG:Ce ceramics show a factor of two smaller RIAC values than LYSO:Ce up to 6.7×10^{15} n_{eq}/cm^2 and 1.2×10^{15} p/cm^2, promising for FCC-hh

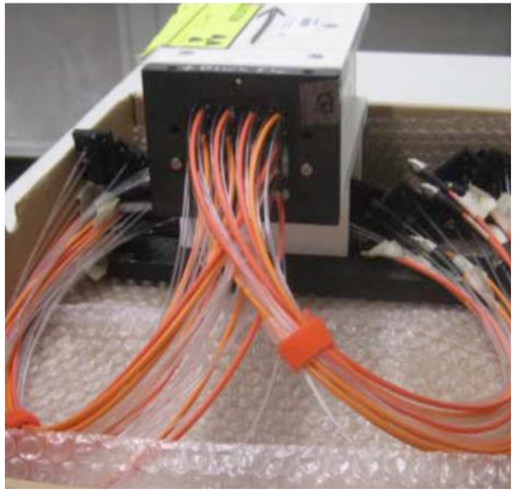


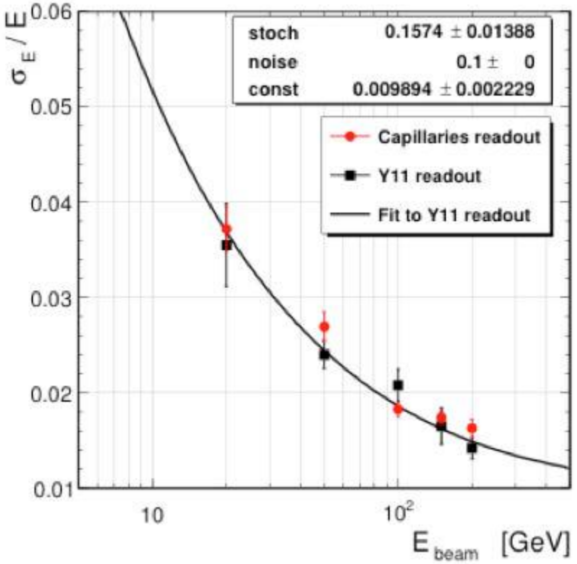




R&D on slow component suppression by Ca co-doping, and radiation hardness by ɣ/p/n

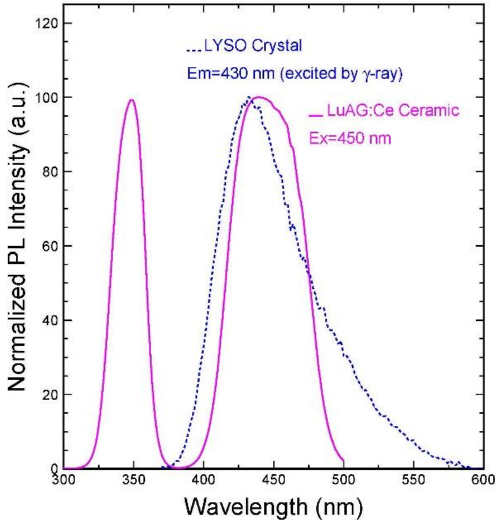
RADiCAL: LYSO/LuAG Shashlik ECAL

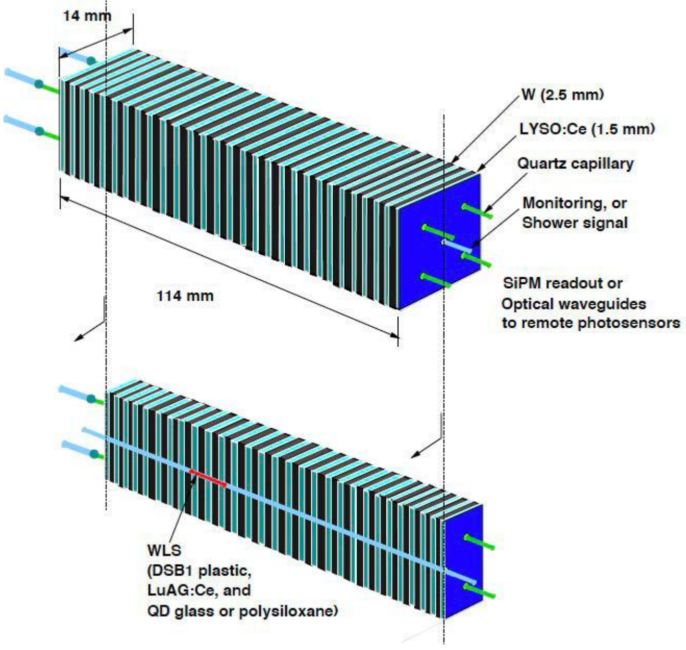


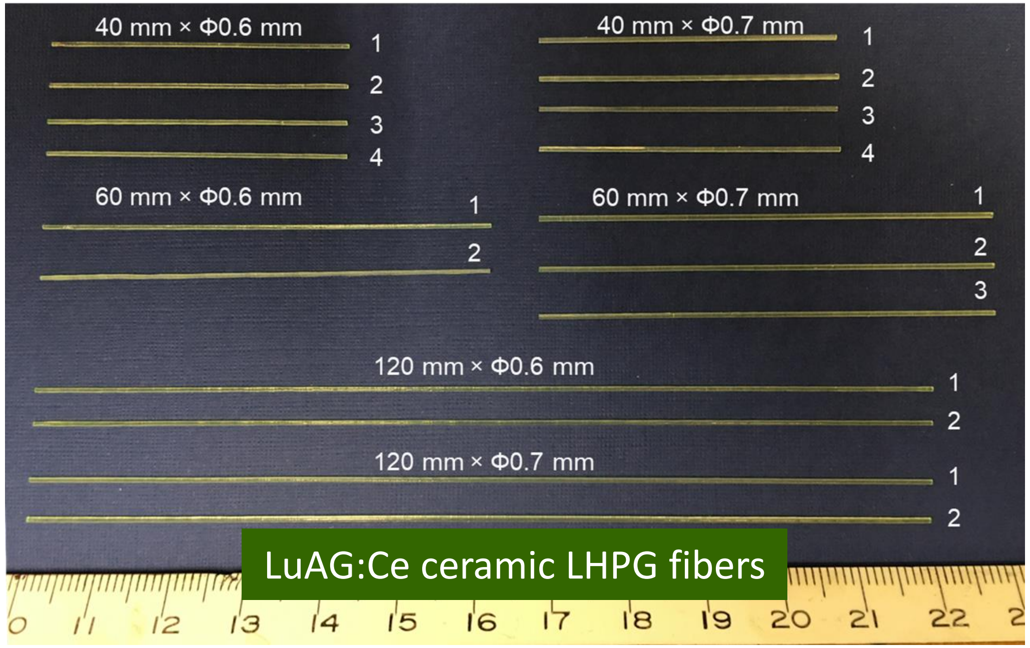


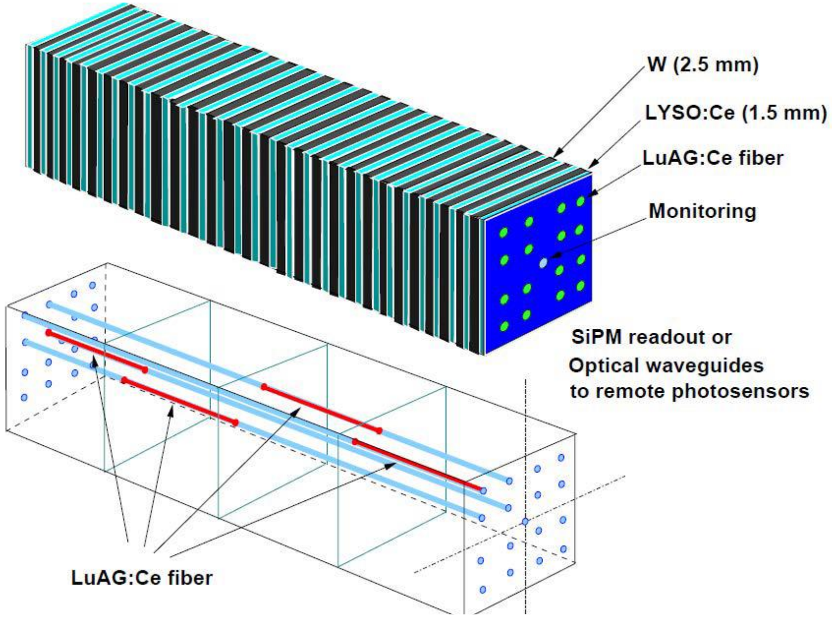
arXiv: 2203.12806

RADiation hard **CAL**orimetry
Reducing light path length to mitigate radiation damage effect
Using radiation hard materials: LuAG:Ce ceramics excitation matches LYSO:Ce emission





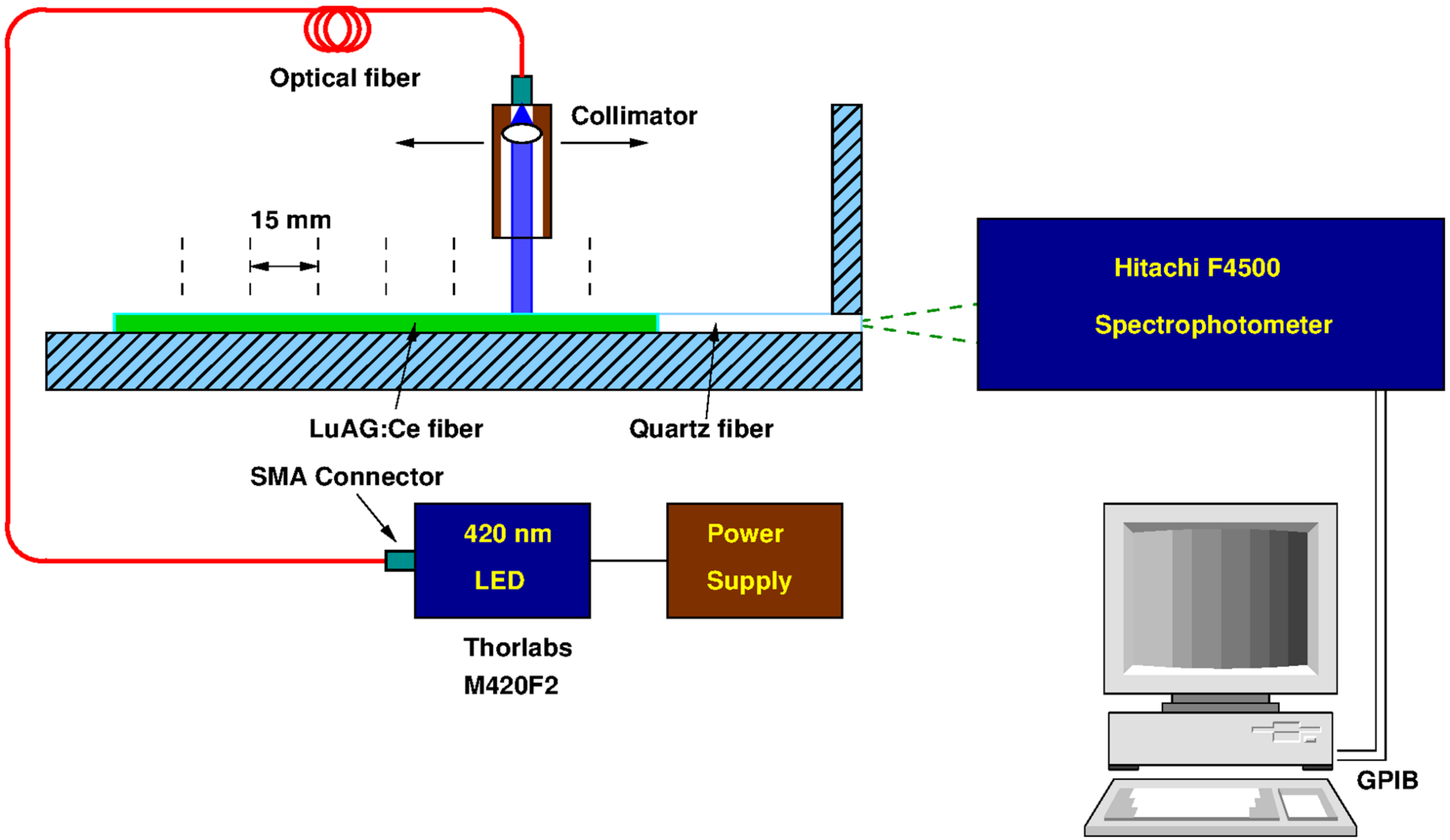


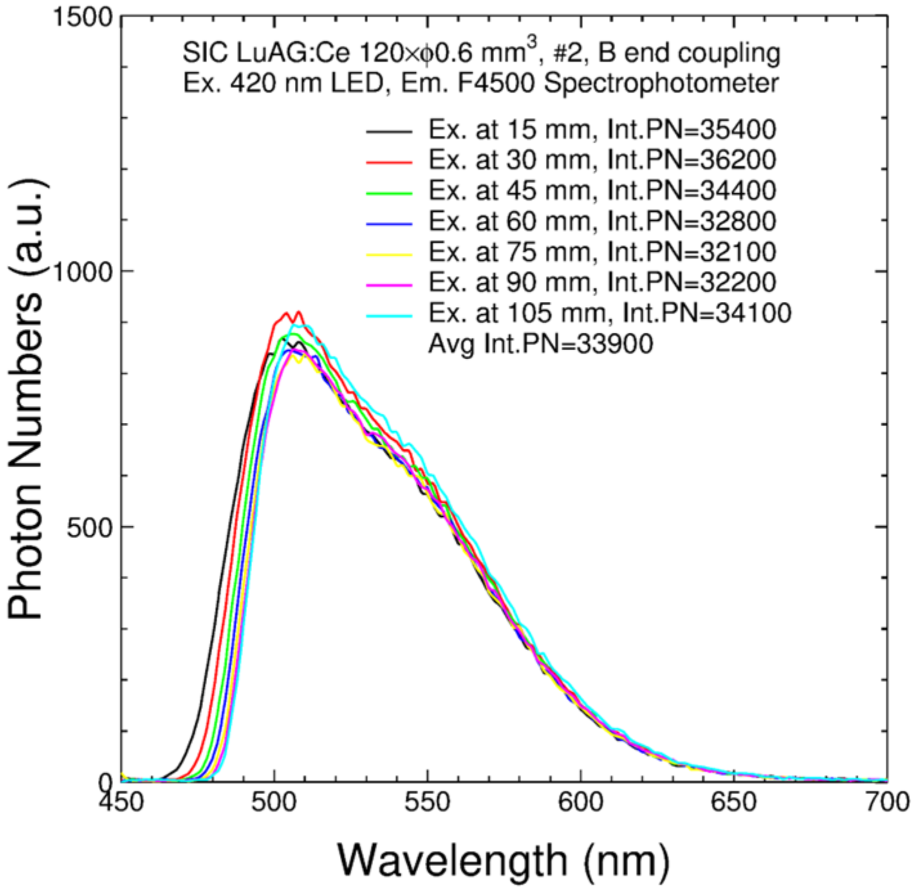


Light Output and Response Uniformity

10.1109/NSS/MIC44867.2021.9875908

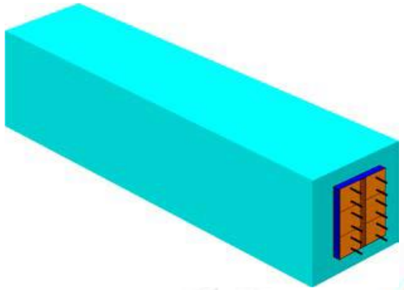
Excellent longitudinal uniformity observed for a Φ0.6 ×120 mm^3 LuAG:Ce ceramic excited by a 420 nm LED at different location, with a solid coupling to a quartz fiber, mimicking its application in RADiCAL





Ultrafast BaF_2:Y Calorimeter for Mu2e-II

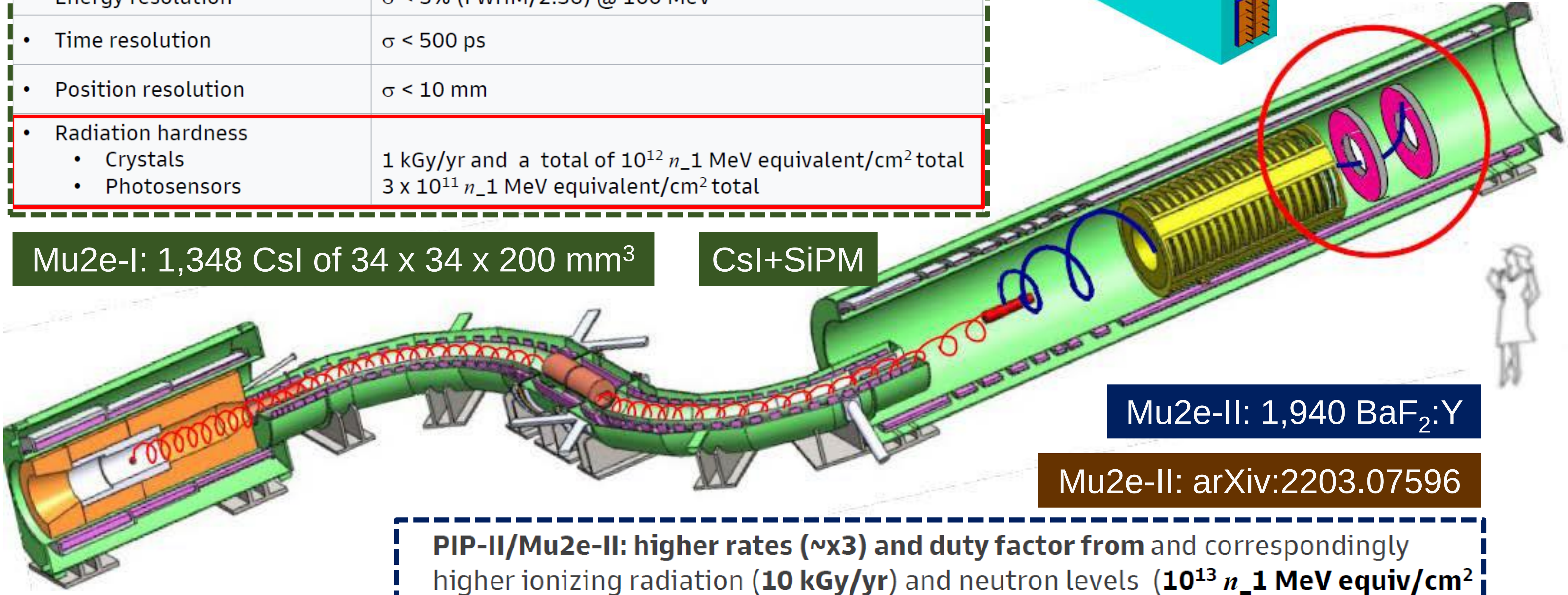
Use ultrafast material to mitigate pile-up



• Energy resolution	σ < 5% (FWHM/2.36) @ 100 MeV
• Time resolution	σ < 500 ps
• Position resolution	σ < 10 mm
• Radiation hardness • Crystals • Photosensors	 1 kGy/yr and a total of 10^{12} n_1 MeV equivalent/cm² total 3 x 10^{11} n_1 MeV equivalent/cm² total

Mu2e-I: 1,348 CsI of 34 x 34 x 200 mm³

CsI+SiPM



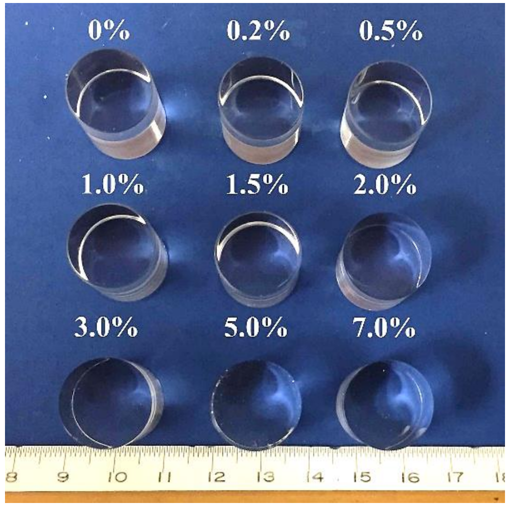
Mu2e-II: 1,940 BaF_2:Y

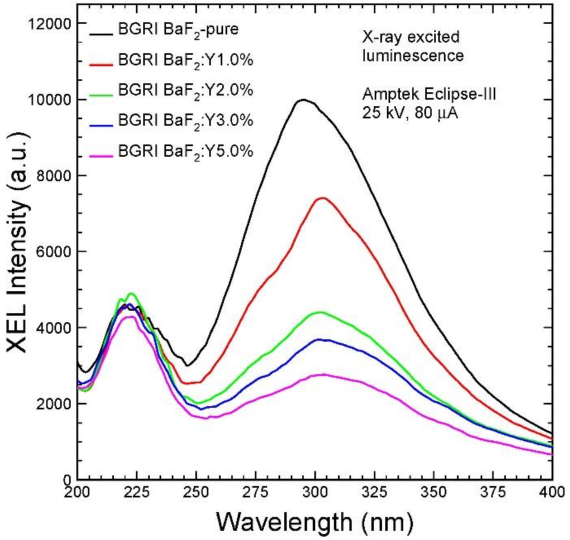
Mu2e-II: arXiv:2203.07596

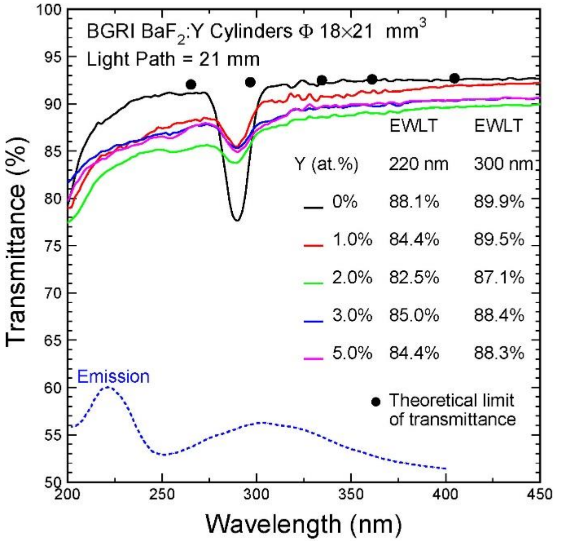
PIP-II/Mu2e-II: higher rates (~x3) and duty factor from and correspondingly higher ionizing radiation (**10 kGy/yr**) and neutron levels (**10^{13} n_1 MeV equiv/cm² total**), which are particularly important at the inner radius of disk 1

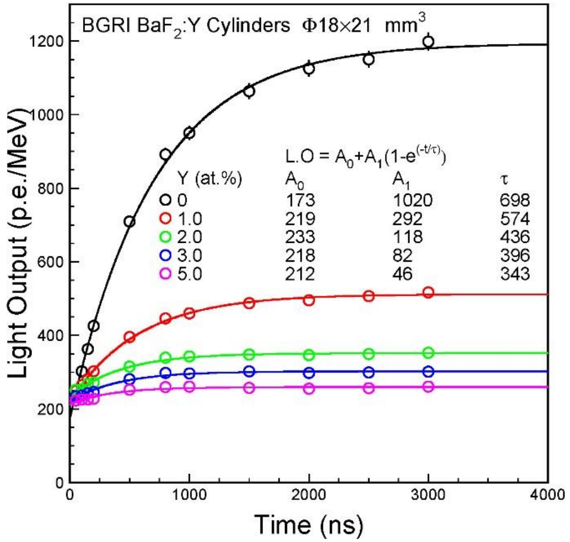
BaF_2:Y for Calorimetry & Imaging

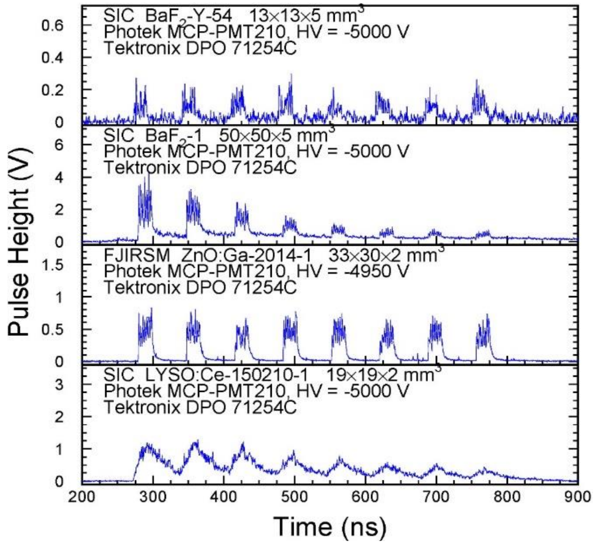
Increased F/S ratio observed in BGRI BaF_2:Y crystals: Proc. SPIE 10392 (2017)

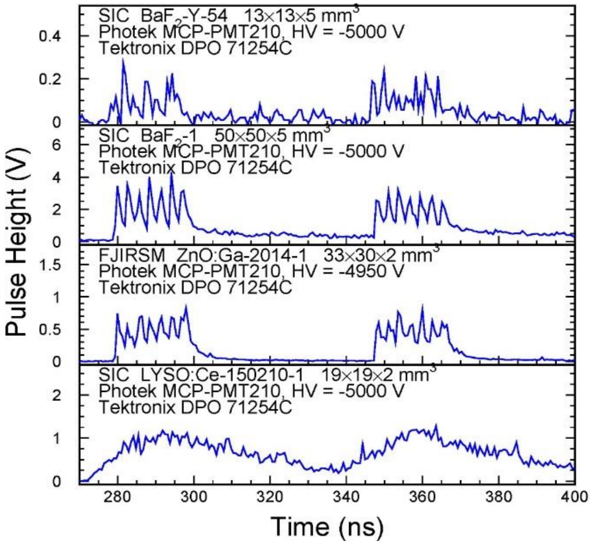


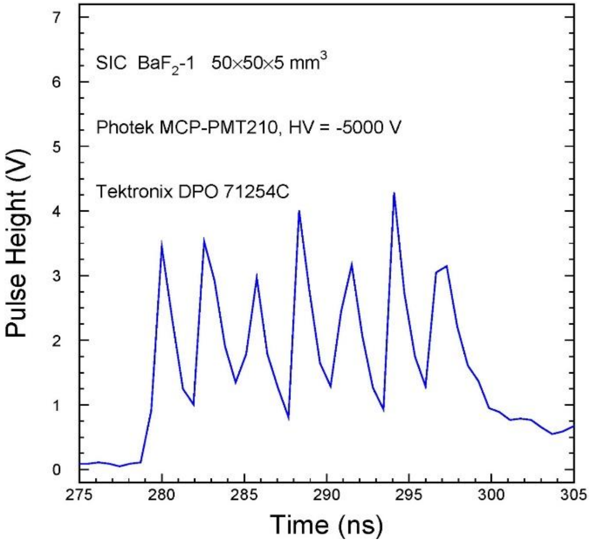












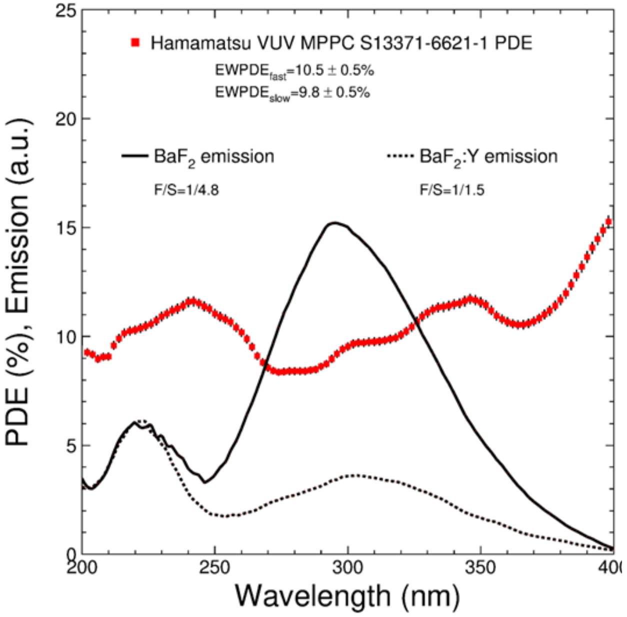
X-ray bunches with 2.83 ns spacing in septuplet are clearly resolved by ultrafast BaF_2:Y and BaF_2 crystals: for GHz Hard X-ray Imaging NIMA 240 (2019) 223-239

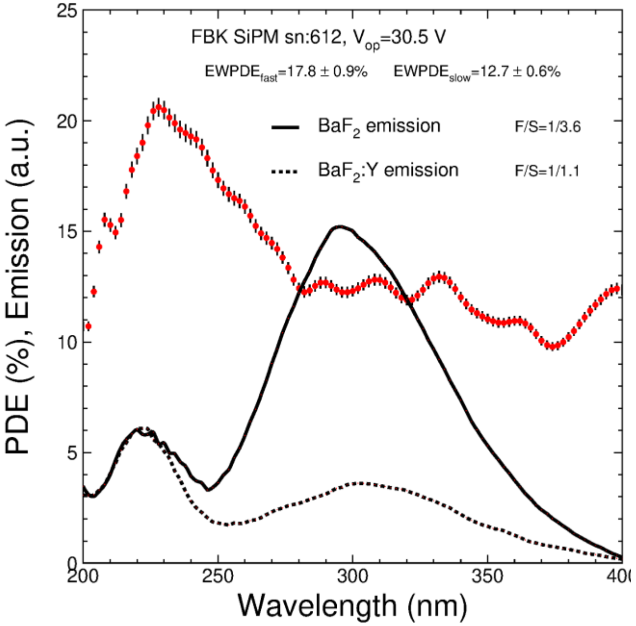
PDE of UV SiPM for BaF_2 and BaF_2:Y

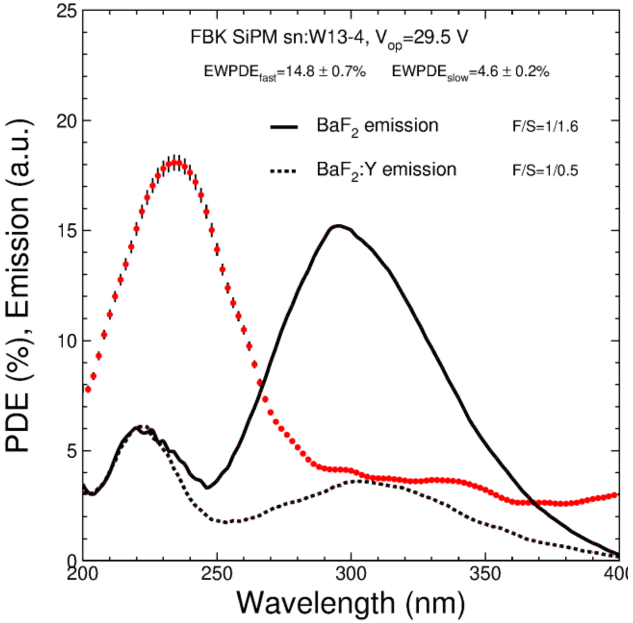
IEEE TNS **69** (2022) 958-964

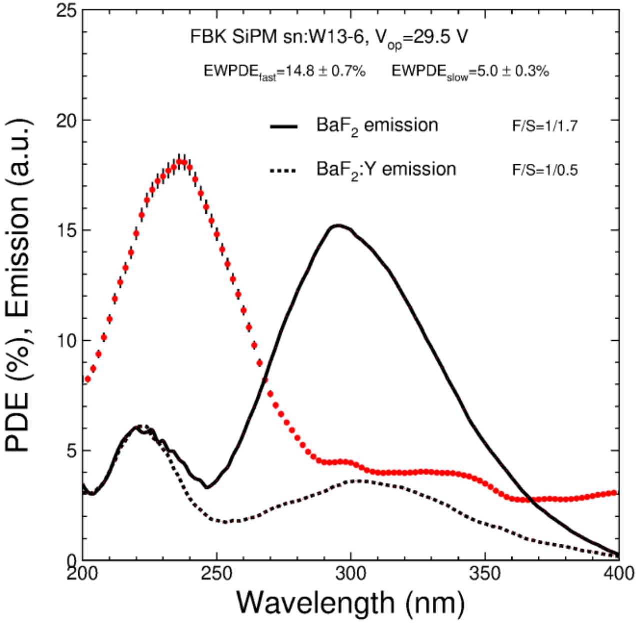
Photodetector	EWPDE$_{fast}$ (%)	EWPDE$_{slow}$ (%)	Relative F/S$_{BaF}$	Relative F/S$_{BaF:Y}$
Hamamatsu MPPC	10.5	9.8	1/4.8	1/1.5
FBK SiPM 2021	17.8	12.7	1/3.6	1/1.1
FBK SiPM 2023-1	14.8	4.6	1/1.6	1/0.5
FBK SiPM 2023-2	14.8	5.0	1/1.7	1/0.5

γ-ray induced readout noise is reduced by BaF_2:Y slow suppression & solar-blind PDE



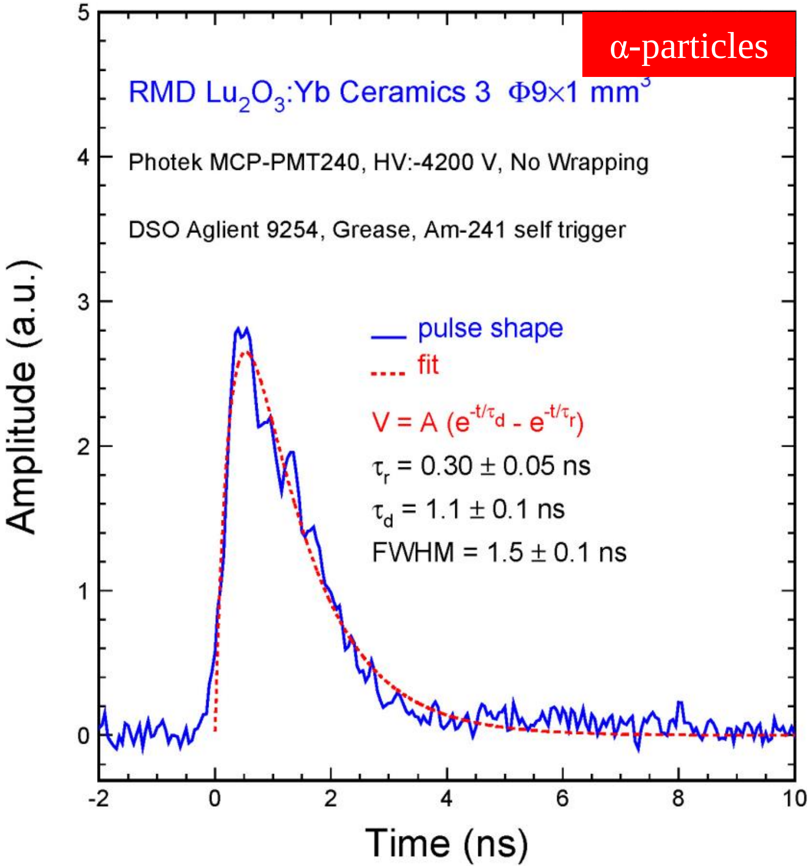


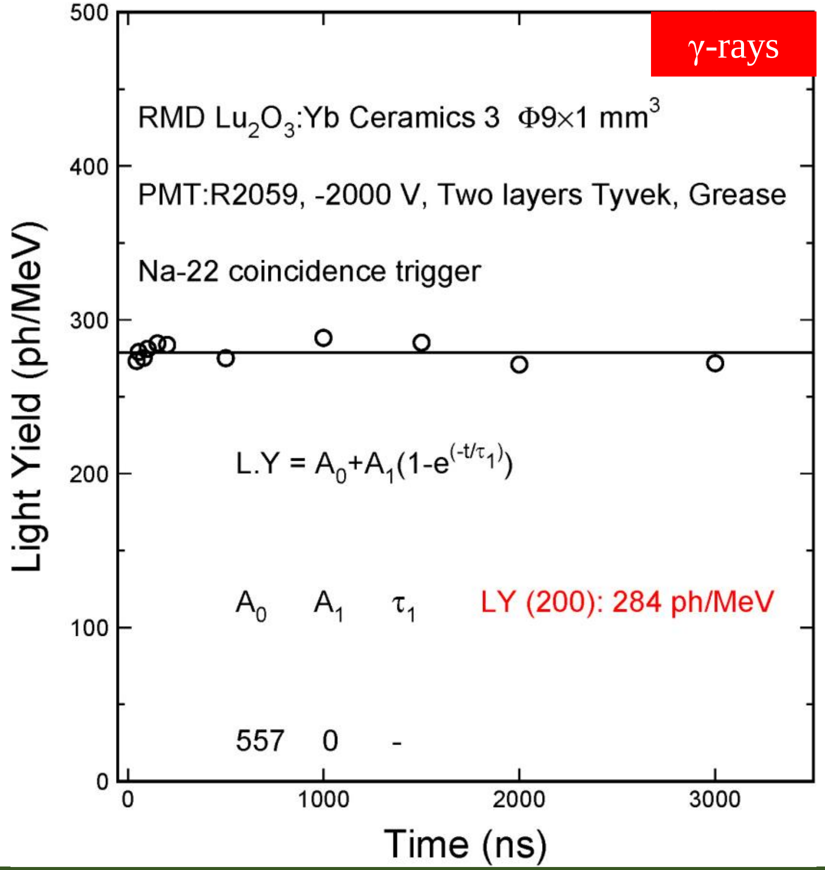


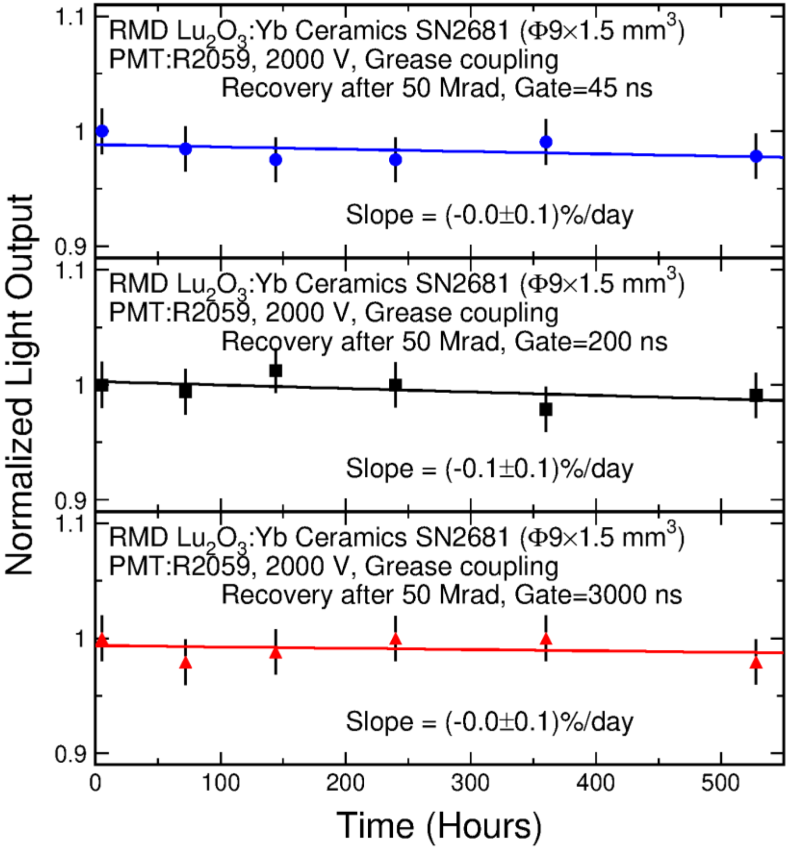


Novel Lu_2O_3:Yb Ceramics

Presented in the NSS2022 conference https://www.its.caltech.edu/~rzhu/talks/NSS22_N21-03.pdf





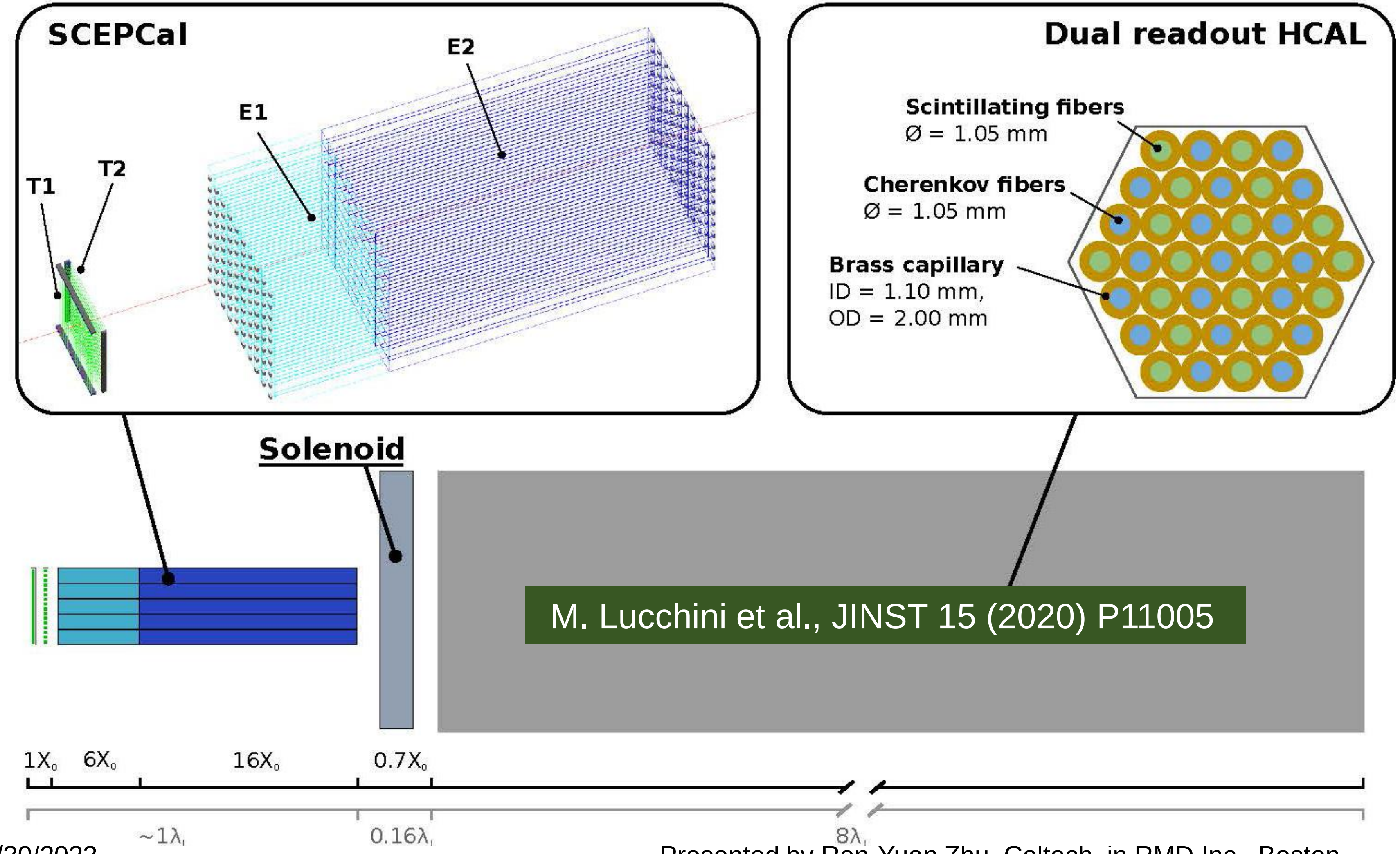


Lu_2O_3:Yb ceramic of 9.4 g/cc shows an ultrafast decay time of **1.1 ns** by Am-241 with negligible slow component observed in integrated light output measurement

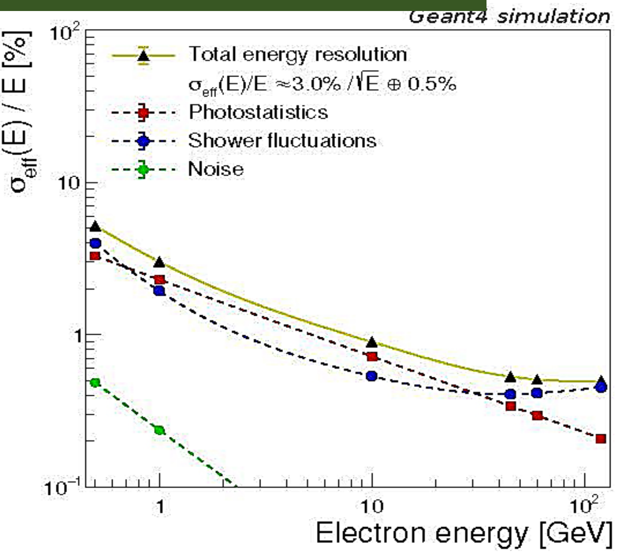
CalVision: Segmented Crystal ECAL

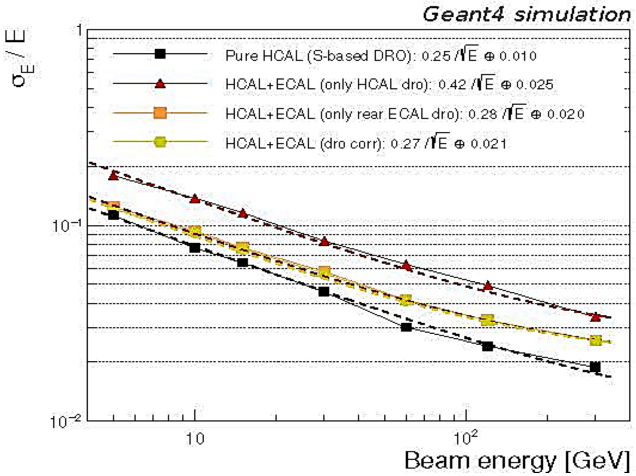
arXiv: 2203.04312

Followed by the IDEA DR HCAL, aiming at both EM and jet resolution

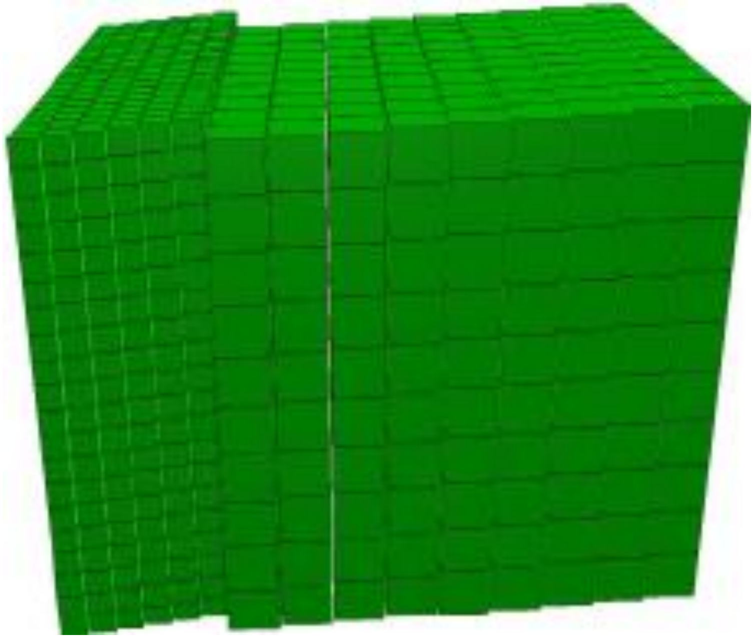


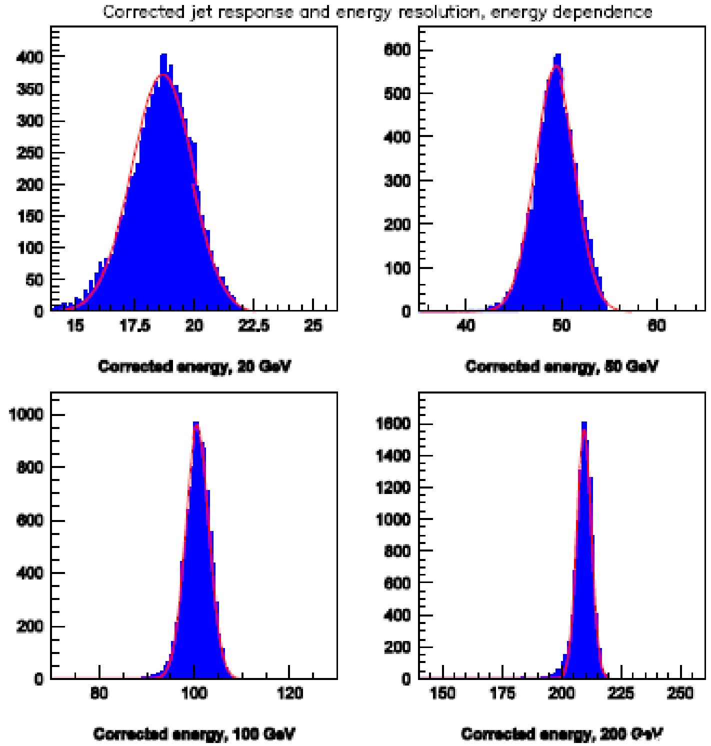
M. Lucchini et al., JINST 15 (2020) P11005



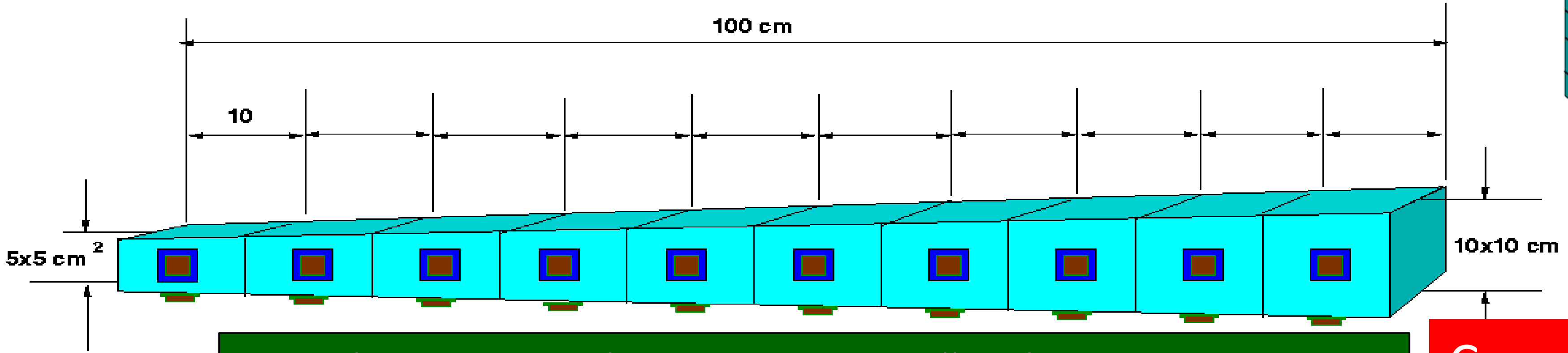


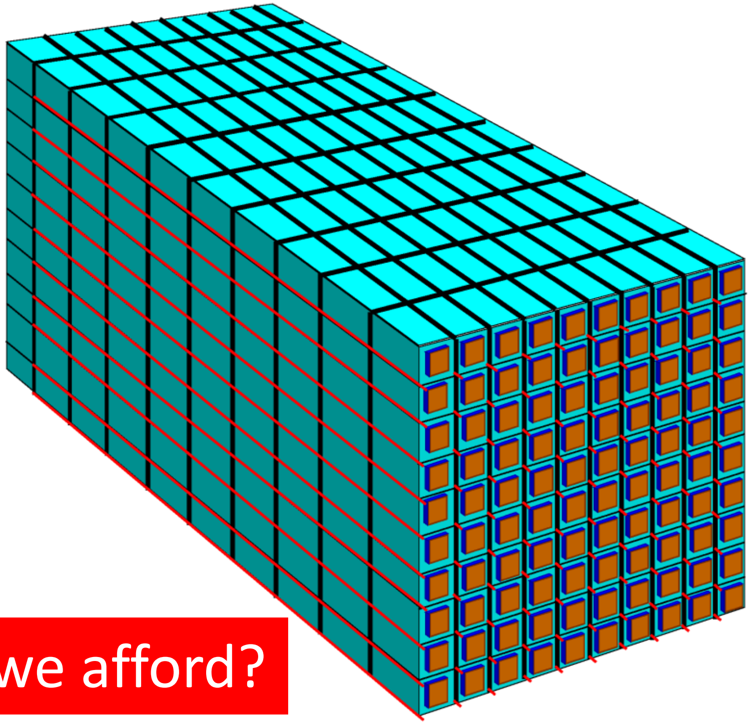
The HHCAL Concept





A. Para, H. Wenzel and S. McGill in Callor2012 Proceedings and A. Benaglia *et al.*, IEEE TNS **63** (2016) 574-579: a jet energy resolution at a level of 20%/√E by HHCAL with dual readout of S/C or dual gate.
M. Demarteau, 2021 CPAD Workshop





R.-Y. Zhu, ILCWS-8, Chicago: a HHCAL cell with pointing geometry

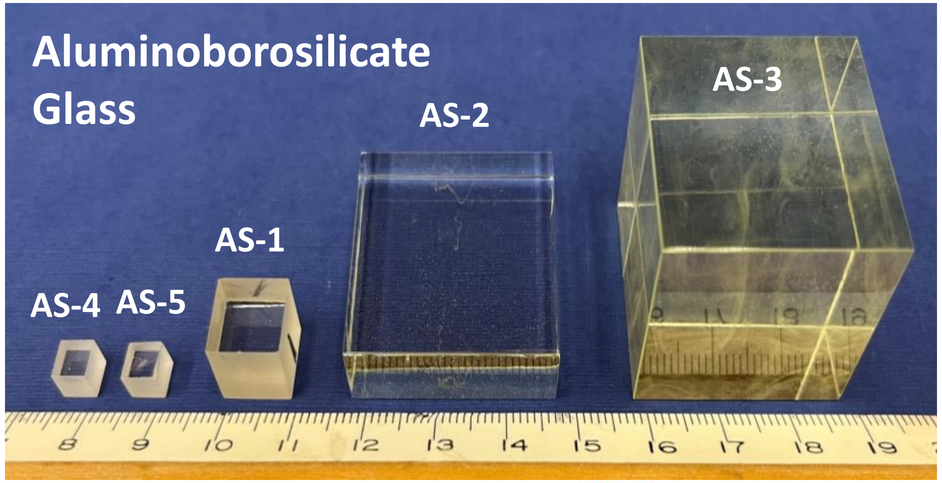
Can we afford?

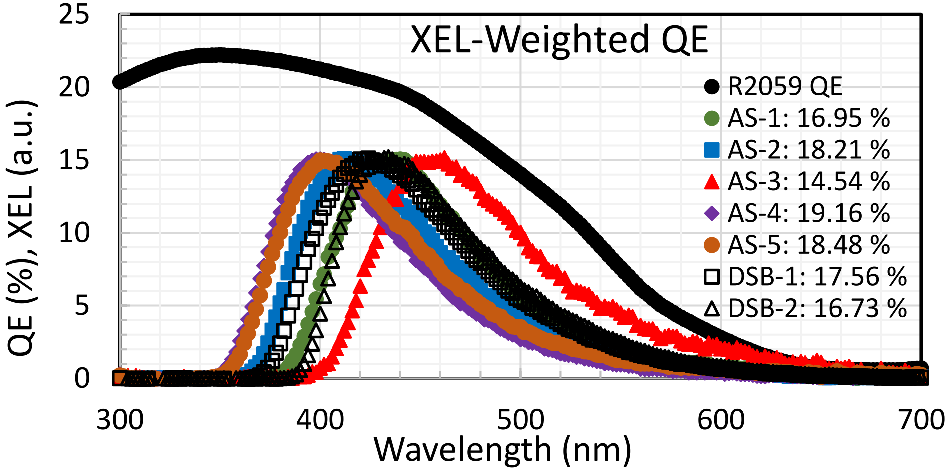
Crystal Cost for CEPC (Mar 2019)

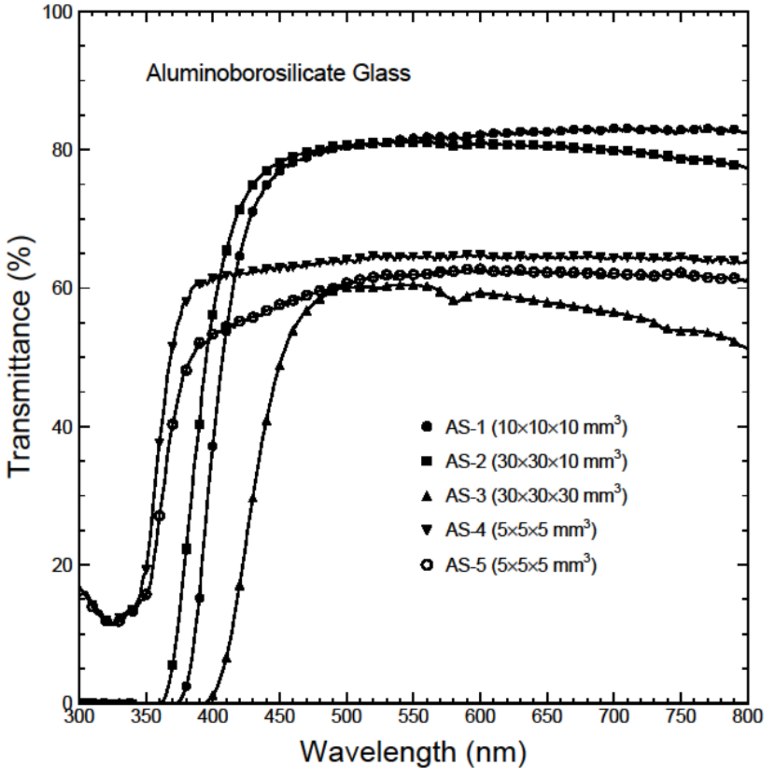
Cost-effectiveness scaled with X_0: PWO, BGO, CsI, BSO, BaF_2:Y, LYSO

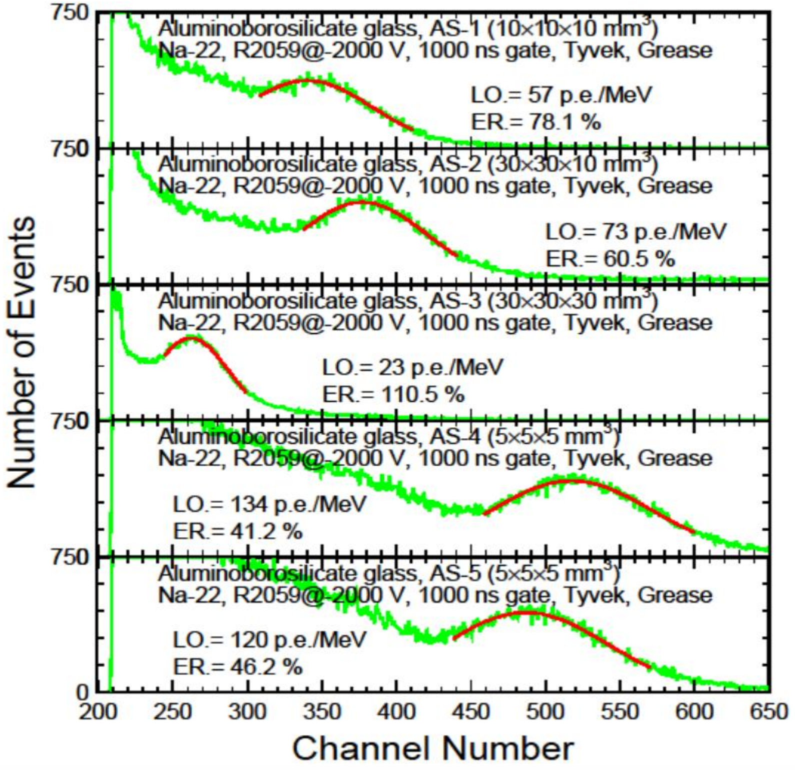
Item	Size (R_MxR_Mx25 X_0)	1 m^3	10 m^3	100 m^3	Scaled to X_0
BGO	22.3×22.3×280 mm	$8/cc	$7/cc	$6/cc	1.23
BaF_2:Y	31.0×31.0×507.5 cm	$12/cc	$11/cc	$10/cc	2.28
LYSO:Ce	20.7x20.7x285 mm	$36/cc	$34/cc	$32/cc	1.28
PWO	20x20x223 mm	$9/cc	$8/cc	$7.5/cc	1.00
BSO	22x22x274 mm	$8.5/cc	$7.5/cc	$7.0/cc	1.29
CsI	35.7x35.7x465 mm	$4.6/cc	$4.3/cc	$4.0/cc	2.09

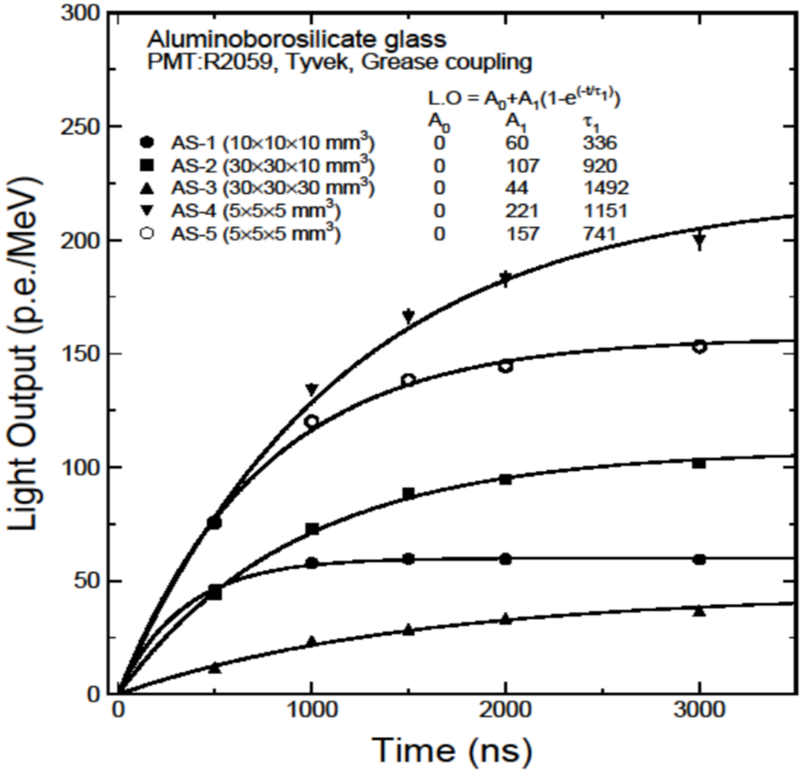
ABS (B_2O_3–SiO_2–Al_2O_3–Gd_2O_3–Ce_2O_3) Glass











Inorganic Scintillators for HHCAL

Presented in the 9/14/2023 CalVision meeting all samples measured at Caltech

	BGO	BSO	PWO	PbF_2	PbFCl	Sapphire:Ti	AFO:Ce Glass	DSB:Ce Glass	ABS:Ce Glass
Density (g/cm^3)	7.13	6.8	8.3	7.77	7.11	3.98	4.6	4.3	6.0
Melting point (℃)	1050	1030	1123	824	608	2040	980[7]	1550	?
X_0 (cm)	1.12	1.15	0.89	0.94	1.05	7.02	2.96	2.58	1.56
R_M (cm)	2.23	2.33	2.00	2.18	2.33	2.88	2.90	3.24	2.49
λ_I (cm)	22.7	23.4	20.7	22.4	24.3	24.2	26.4	30.9	24.2
Z_{eff} value	71.5	73.8	73.6	76.7	74.7	11.1	41.4	49.5	56.6
dE/dX (MeV/cm)	8.99	8.59	10.1	9.42	8.68	6.75	6.84	6.1	8.0
Emission Peak[a] (nm)	480	470	425 420	\	420	300 750	365	420	400
Refractive Index[b]	2.15	2.68	2.20	1.82	2.15	1.76	?	?	?
LY (ph/MeV)[c]	7,500	1,500	130	\	150	7,900	450	1,360	1,150
Decay Time[a] (ns)	300	100	30 10	\	3	300 3200	40	500	740
d(LY)/dT (%/°C)[c]	-0.9	?	-2.5	\	?	?	?	0.3	?
Cost ($/cc)	6.0	7.0	7.5	6.0	?	0.6	2.0	2.0	<1

Summary

- The HL-LHC and FCC-hh require fast and radiation hard inorganic scintillator.
- **RADiCAL** proposes an ultra-compact, fast timing and longitudinally segmented shashlik calorimeter with LuAG:Ce ceramics as wavelength shifter for LYSO:Ce crystals. R&D is on-going to suppress slow components in LuAG:Ce.
- **Mu2e-II** considers ultrafast BaF_2:Y calorimeter. R&D is on radiation hardness of BaF_2:Y and solar-blind SiPM. Industry is developing ultrafast Lu_2O_3:Yb ceramics.
- **CalVision** proposes a dual readout longitudinally segmented crystal ECAL combined with the IDEA HCAL promising excellent EM and Hadronic resolutions for the proposed lepton Higgs factory.
- Homogeneous HCAL (**HHCAL**) promises the best jet mass resolution by total absorption. Novel cost-effective heavy scintillating glass is under development.

Acknowledgements: DOE HEP Award DE-SC0011925

R&D On-going at Caltech

Fast/ultrafast, radiation hard and cost-effective heavy scintillators

Bright, fast and radiation hard inorganic scintillators for the severe radiation environment expected by the proposed FCC_{hh}. YAG, LuAG, GGAG, GYAG and GLuAG suffer from slow scintillation component.

Ultrafast inorganic scintillators: Cross-luminescence. Wide gap semiconductor-based scintillators with sub-ns decay time and quantum confinement-based inorganic $CsPbX_3$ (X = Cl, Br, I, mixed Cl/Br and Br/I), halide perovskite quantum dots may help to break the ps timing barrier for future HEP TOF.

Dense, UV-transparent, cost-effective heavy inorganic scintillators for the homogeneous hadron calorimeter (HHCAL) concept for the Higgs factory.

Compact UV sensitive photodetectors with sufficient dynamic range for ultrafast calorimeters.

Presented in the DRC9 round table discussion in 2023 CPAD Workshop, SLAC